ARPES part I

Adam Kamiński

Ames Laboratory and Iowa State University

Cliff G. Olson

(July 6th, 1942 - February 21st, 2009)

Stoughton- Clifford Gerald Olson died on Saturday February 21, 2009 at his home in the Town of Dunn at the age of 66. He was born July 6, 1942 in Long Prairie, MN to Clifford and Ethel Olson of Osakis, MN. He is survived by his wife Donna M. Sansome Olson, whom he married in St. Paul, MN in 1965. He is further survived by a son, Allen (Melissa); a daughter Lynnette; a sister, Jean (Harlan) Chapman, of Schiocton, WI; two grandchildren, Alexander and Ella; and several nieces and nephews. Clifford went to Hamline University in St. Paul for his B.S. degree in 1964 and Iowa State University in Ames for his PhD in physics in 1970. He worked in solid state physics research for Ames Lab throughout his career, with his research being done at the Physical Sciences Lab in Stoughton. A large number of his projects were collaborations with scientists from throughout the United States, Canada, Korea and several European countries. He was awarded the Professional and Scientific Excellence Award in 1996 from Iowa State University. He found photography, woodworking and Donna's embroidery an escape from his research. A memorial service will be held on Thursday, February 26, 2009 at 11:00 am at the Olson Holzhuter-Cress Funeral Home in Stoughton, with Rev. Clyde Cross officiating, followed by a reception at the Stoughton American Legion Post #59 on North Page St. The family will greet friends at the Funeral Home on Wednesday from 5:00 to 7:00 pm. Memorials may be made in Clifford's name to Second Harvest, or to the charity of your choice.

Outline:

PART I

- Instrumentation
- Principles of ARPES technique
- Basic properties: band structure and Fermi suface and how to read the data

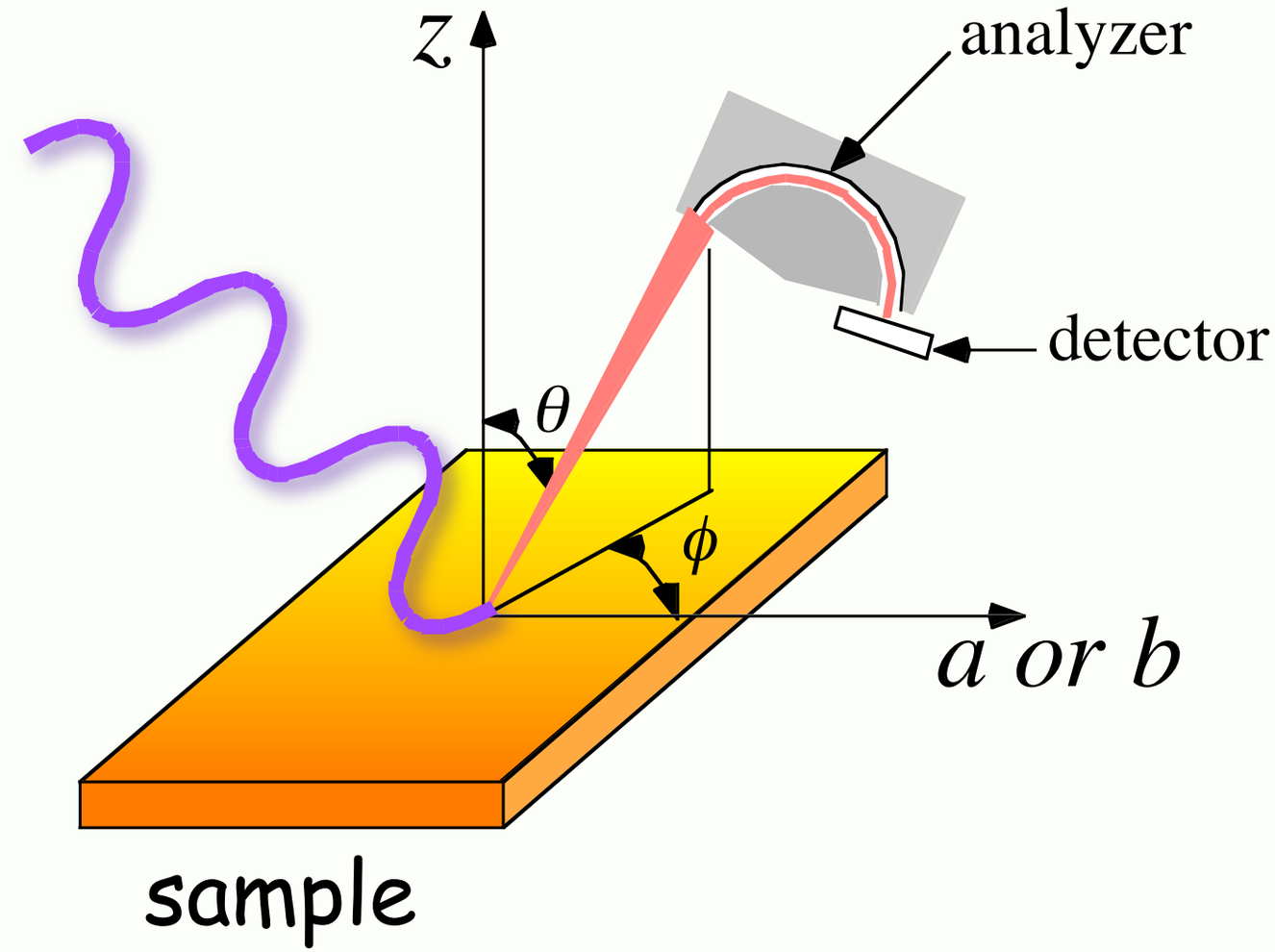
PART II

Properties measured by ARPES: energy gaps, quasiparticle lifetime, collective modes

PART III

Discussion of recent, interesting results: superconductivity, magnetism, charge density waves etc

ARPES experiment



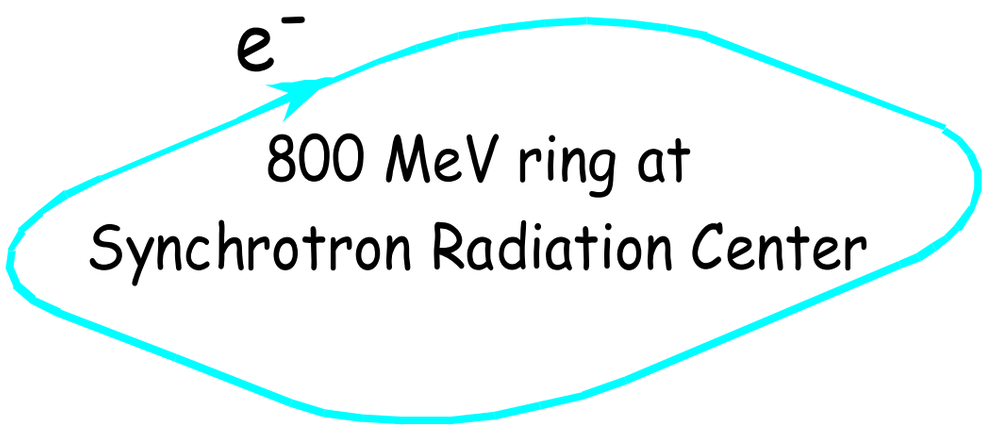
Vacuum UV sources

Energy range: 7 eV - 1000 eV (or 1 nm to 240 nm).

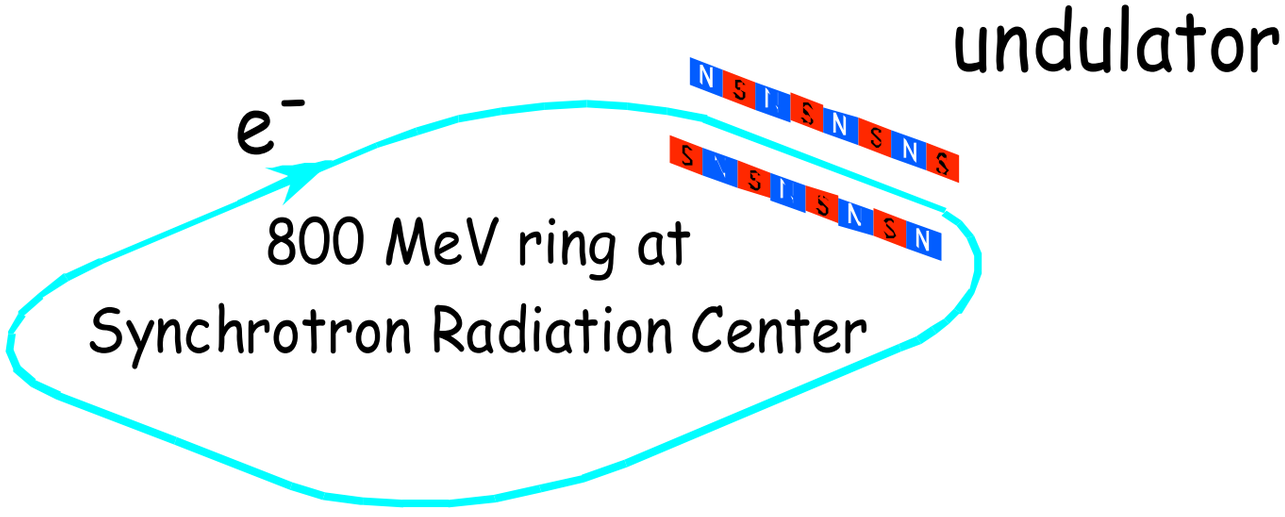
Photons in this energy range are asily absorbed in air with mean free path from few cm to less than 1 mm.

Monochromatic, tightly focused beams are required

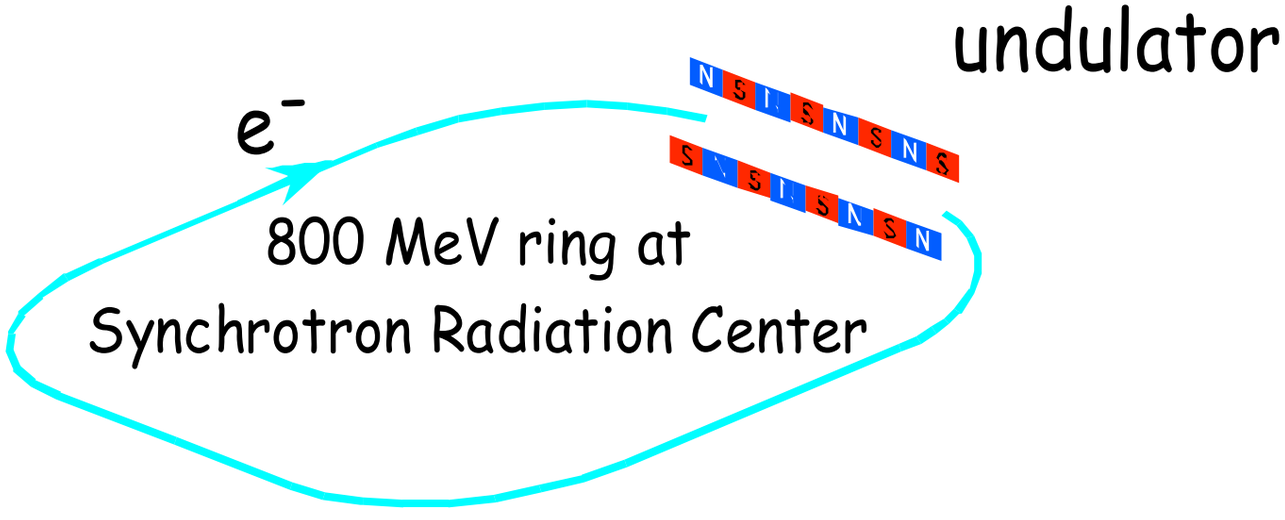
VUV light from the synchrotron



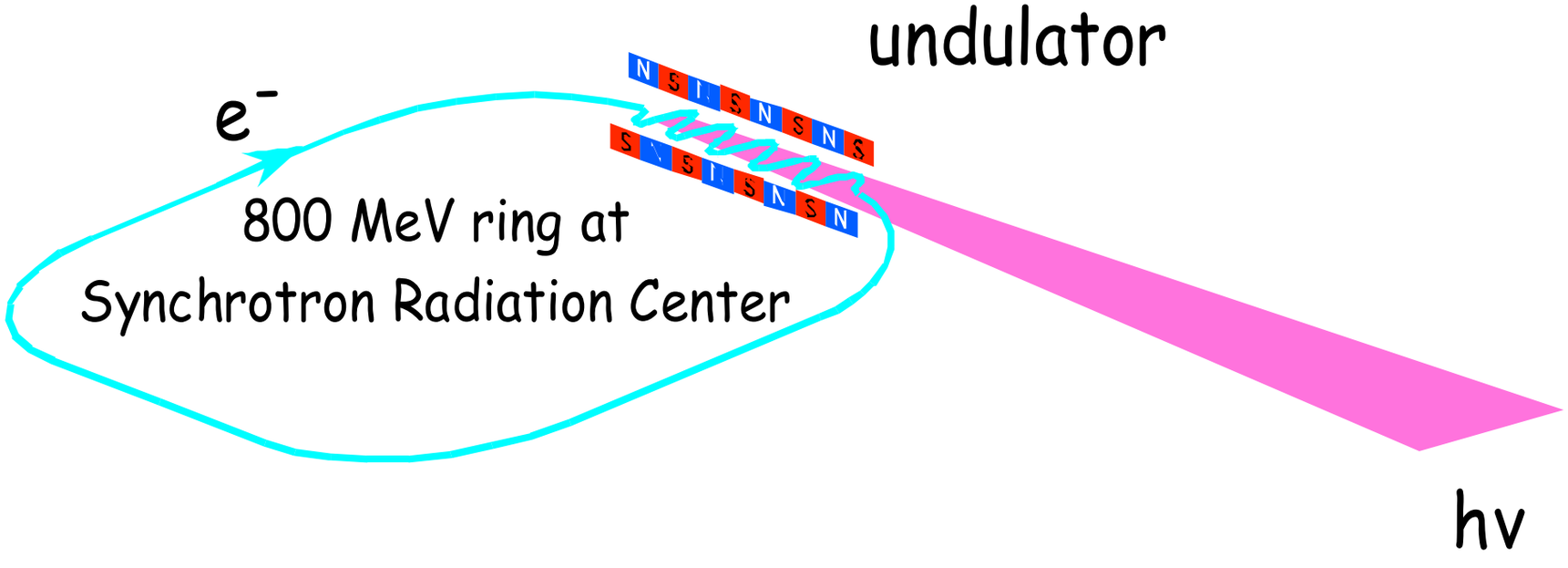
VUV light from the synchrotron



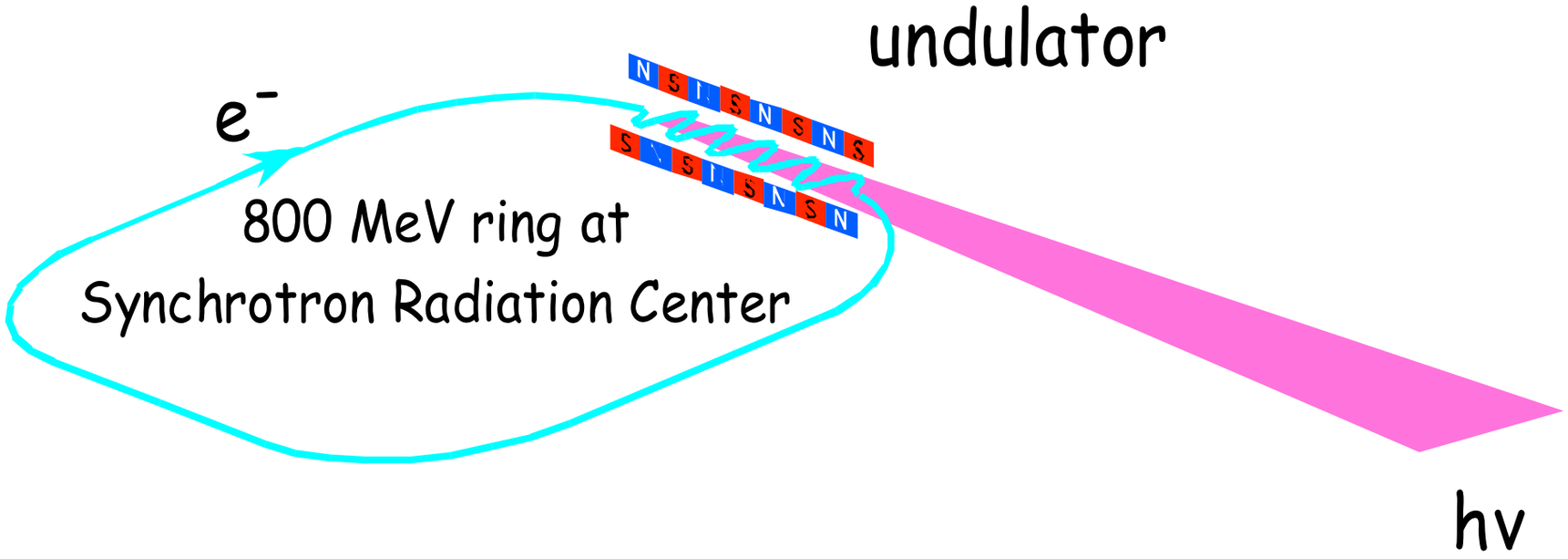
VUV light from the synchrotron



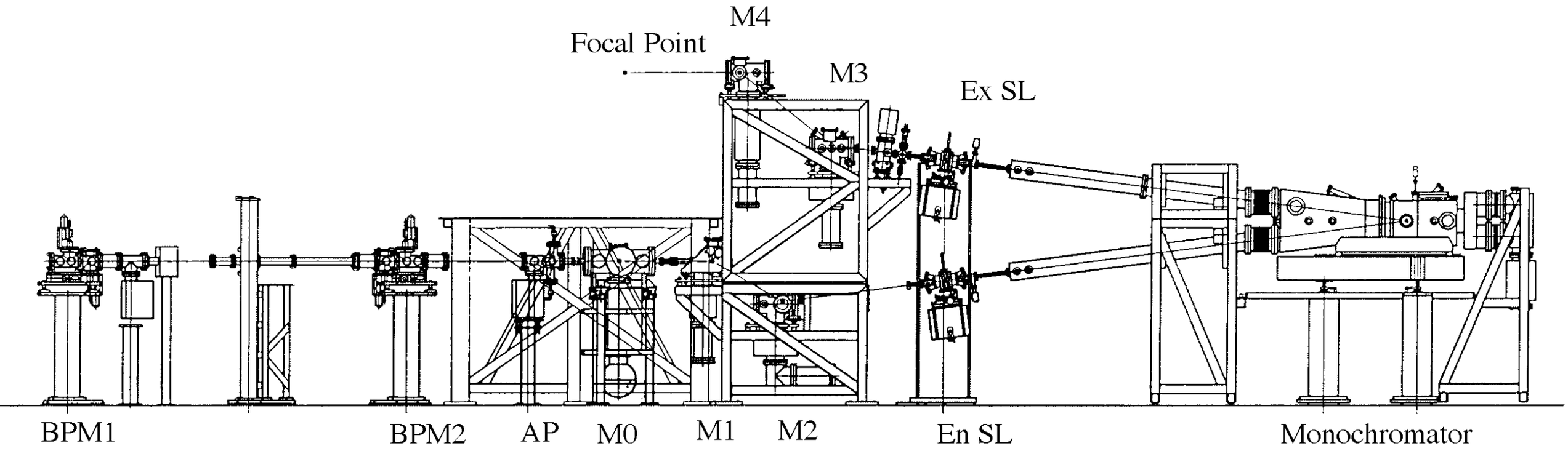
VUV light from the synchrotron



VUV light from the synchrotron



U1 beamline



Side View

Aladdin storage ring

011
4M NIM
SRC/PRT

013
AMOCO-TGM
SRC

021
SEYA
SRC

023
MMC
UW

031
IR
SRC

032
ES-1
CNTech

033
8M HRM
SRC

041
EUV
CNTech

041
Wadsworth
SRC

041
VLS-PGM
SRC

042
6M TGM
SRC

043
MARK V
GRASSHOPPER
SRC

051
MULTI-LAYER
UW

053
ERG-SEYA
LSU/MSU

061
WHITE LIGHT
SRC

Ames
ERG/SEYA

SRC PERMANENT
MAGNET UNDULATOR
(U2)

SRC PERMANENT
MAGNET UNDULATOR
(U3)

123
10M TGM
SRC

108 MeV MICROTRON

SRC/PRT ELECTRO-
MAGNETIC UNDULATOR
(U1)

N

MAIN RF CAVITY

062
6M TGM
SRC

121
ES-5
CNTech

SUSS 200/2M
CLEANROOM

POWER
ROOM

IOWA STATE
ELECTROMAGNETIC
UNDULATOR
(U4)

4TH HARMONIC
CAVITY

073
EDUCATIONAL
OUTREACH
SRC

113
ES-6
CNTech

122
ES-0
CNTech

SAL MOD 4
CLEANROOM

112
ES-2
CNTech

111
ES-4
CNTech

ISU beamline U4

103
MARK II
GRASSHOPPER
SRC

072
ERG-SEYA
SRC/PRT

083
AL. SEYA
SRC

101
NIM
ISU

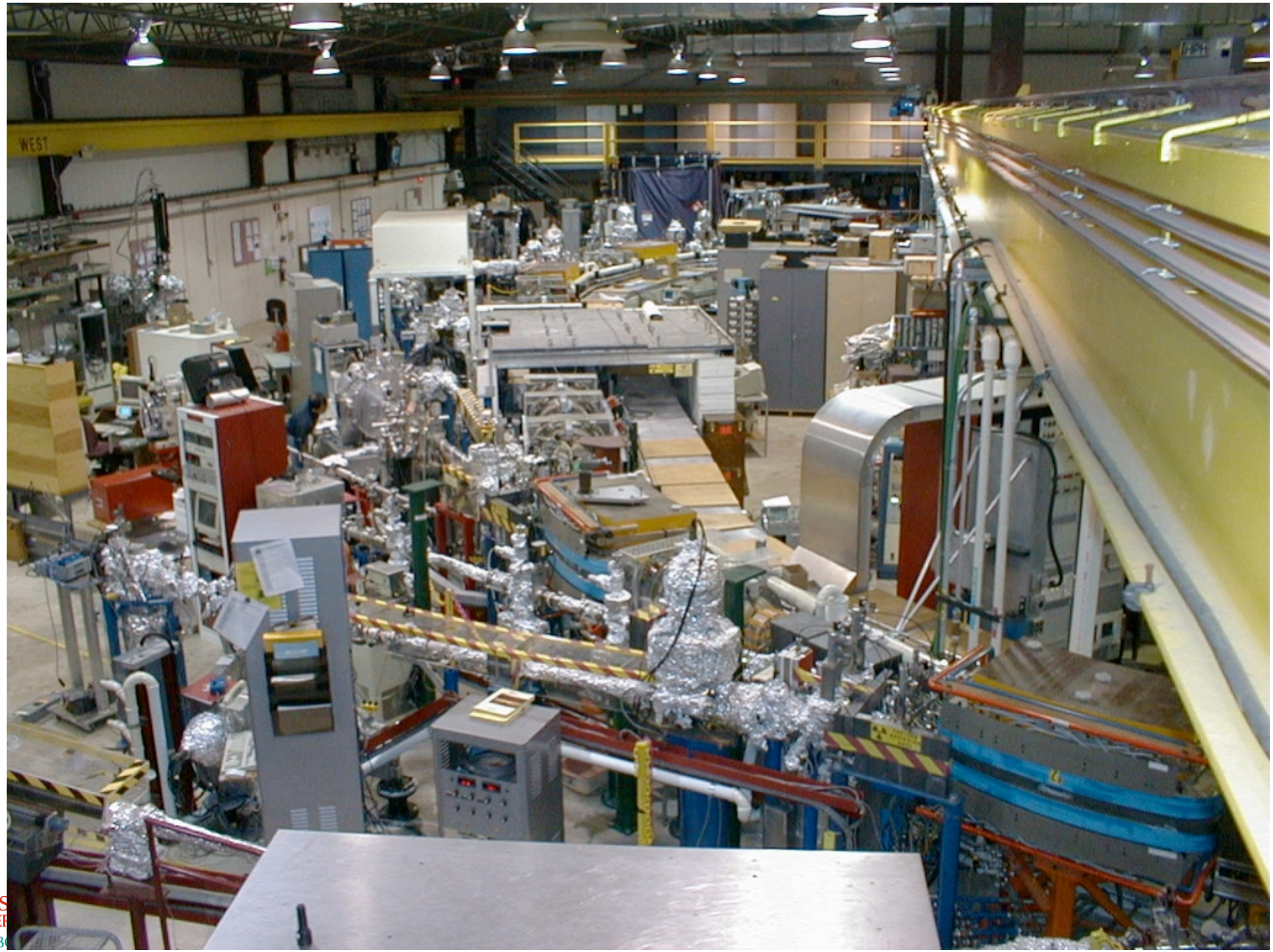
093
DOUBLE CRYSTAL
CANADA

091
GRASSHOPPER
CANADA

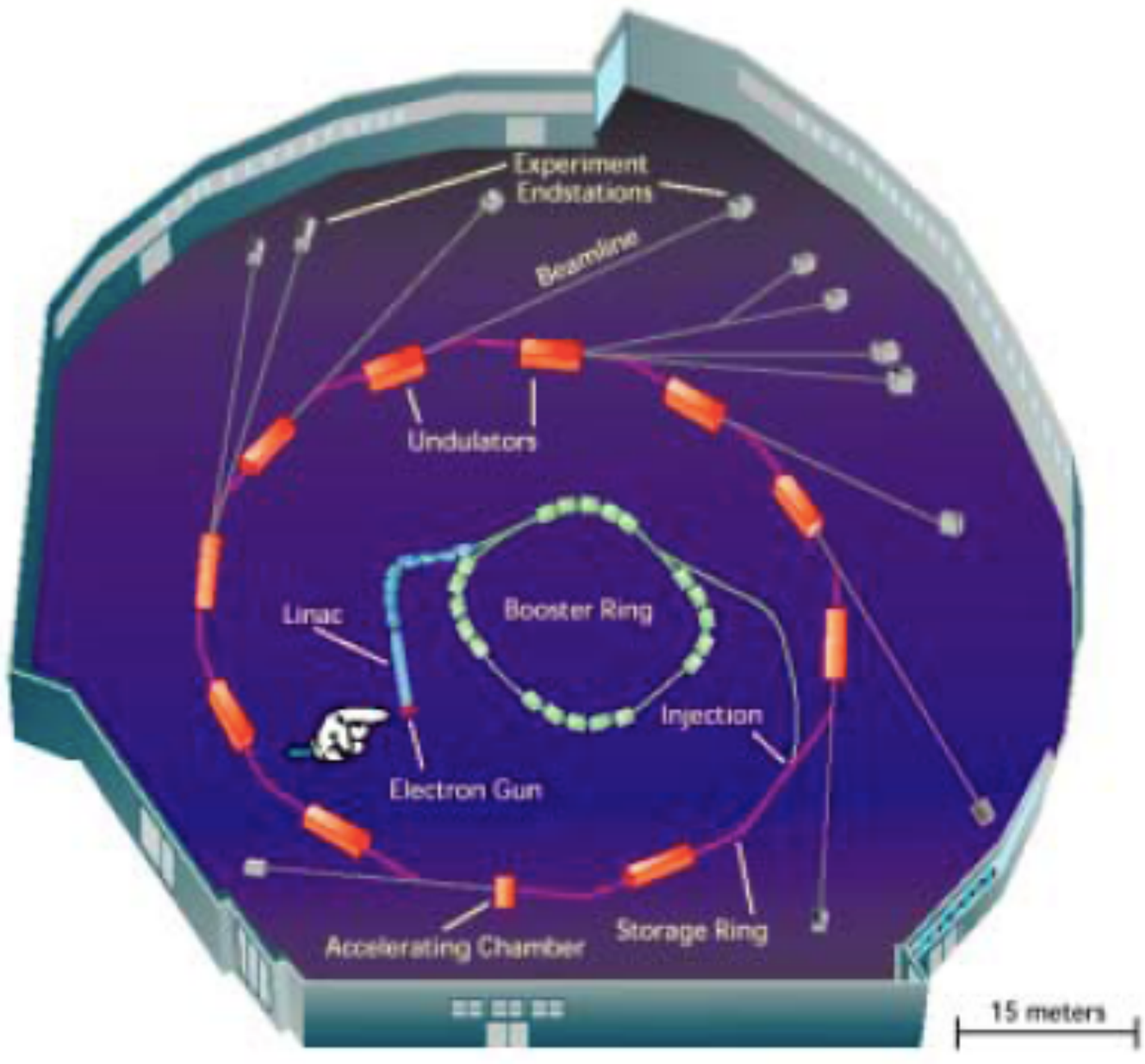
081
4M NIM
SRC

071
PGM
SRC

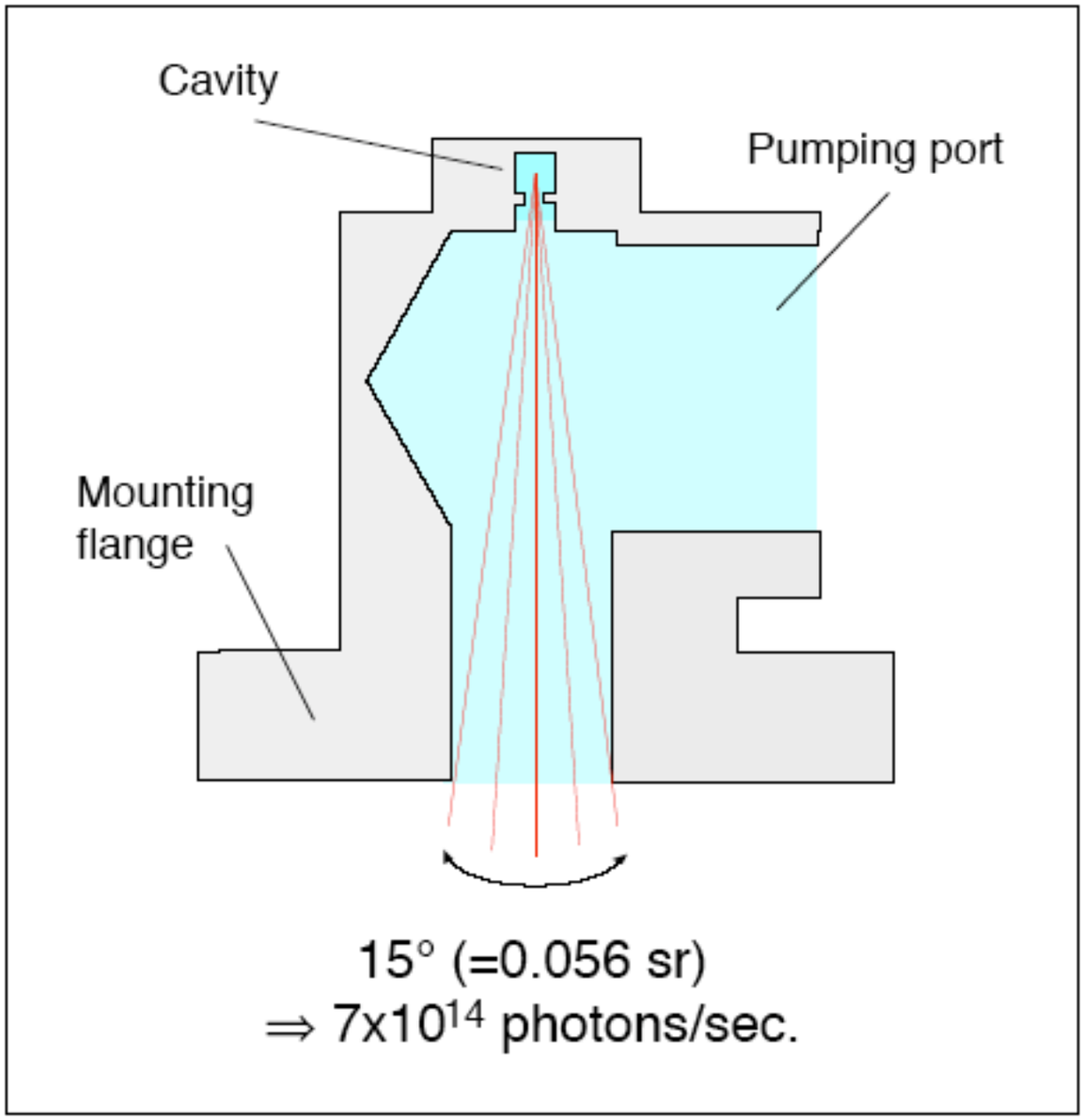
Alladin at SRC



Advanced Light Source at Lawrence Orlando Berkeley National Laboratory


Experiment
Endstations
Beamline
Undulators
Linac
Booster Ring
Injection
Electron Gun
Accelerating Chamber
Storage Ring
15 meters

Helium ECR lamp

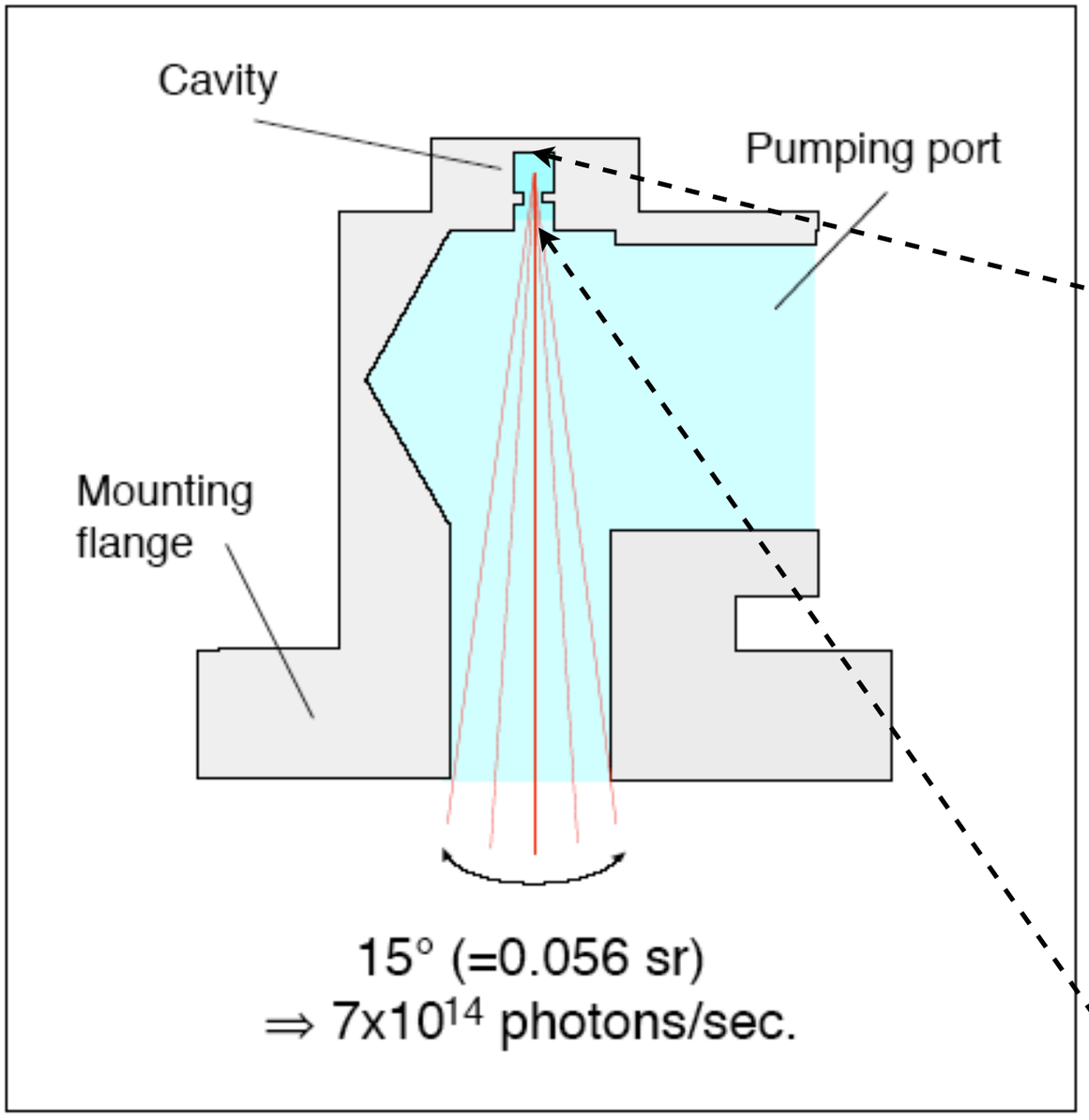


He I - 21.218 eV

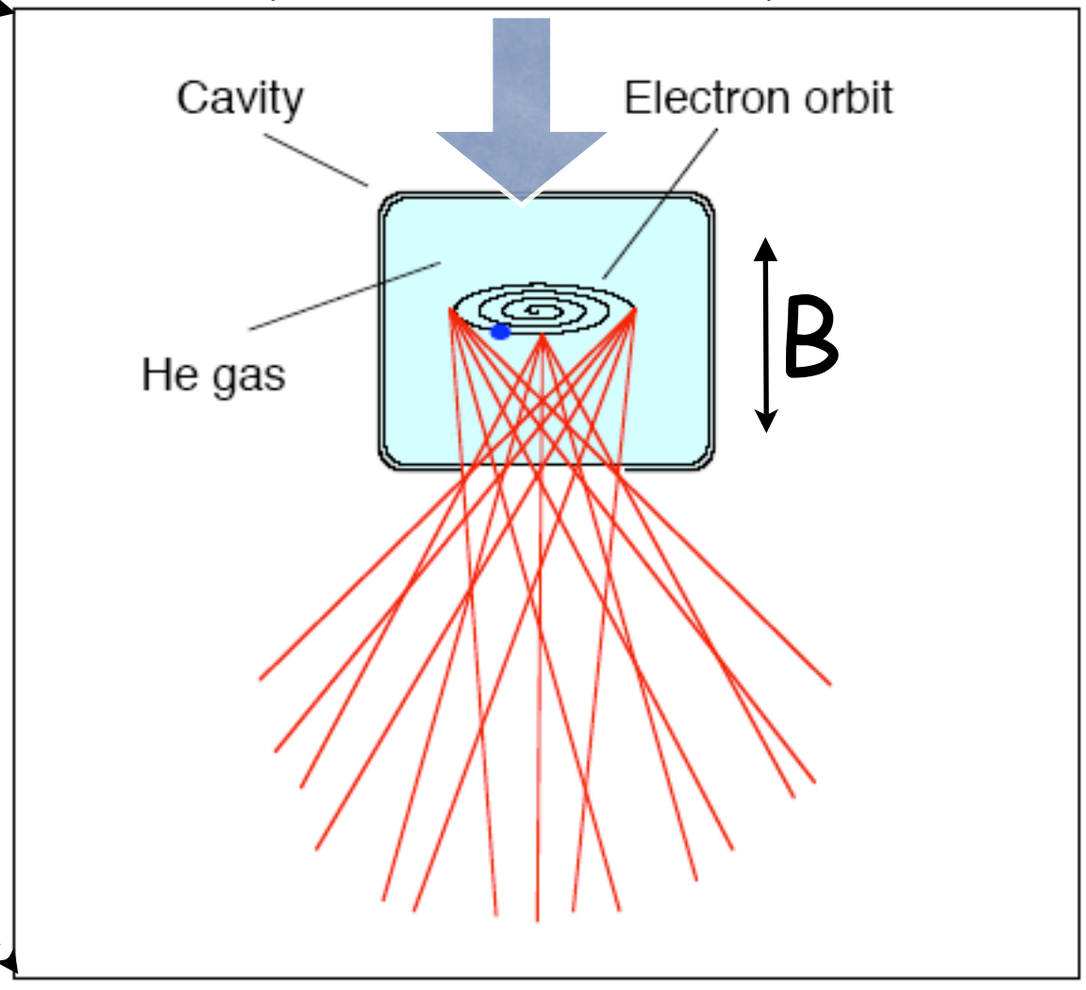
He I - 23.087 eV

He II - 40.823 eV

Helium ECR lamp



microwaves
(250 W @ 10 GHz)



He I - 21.218 eV

He I - 23.087 eV

He II - 40.823 eV

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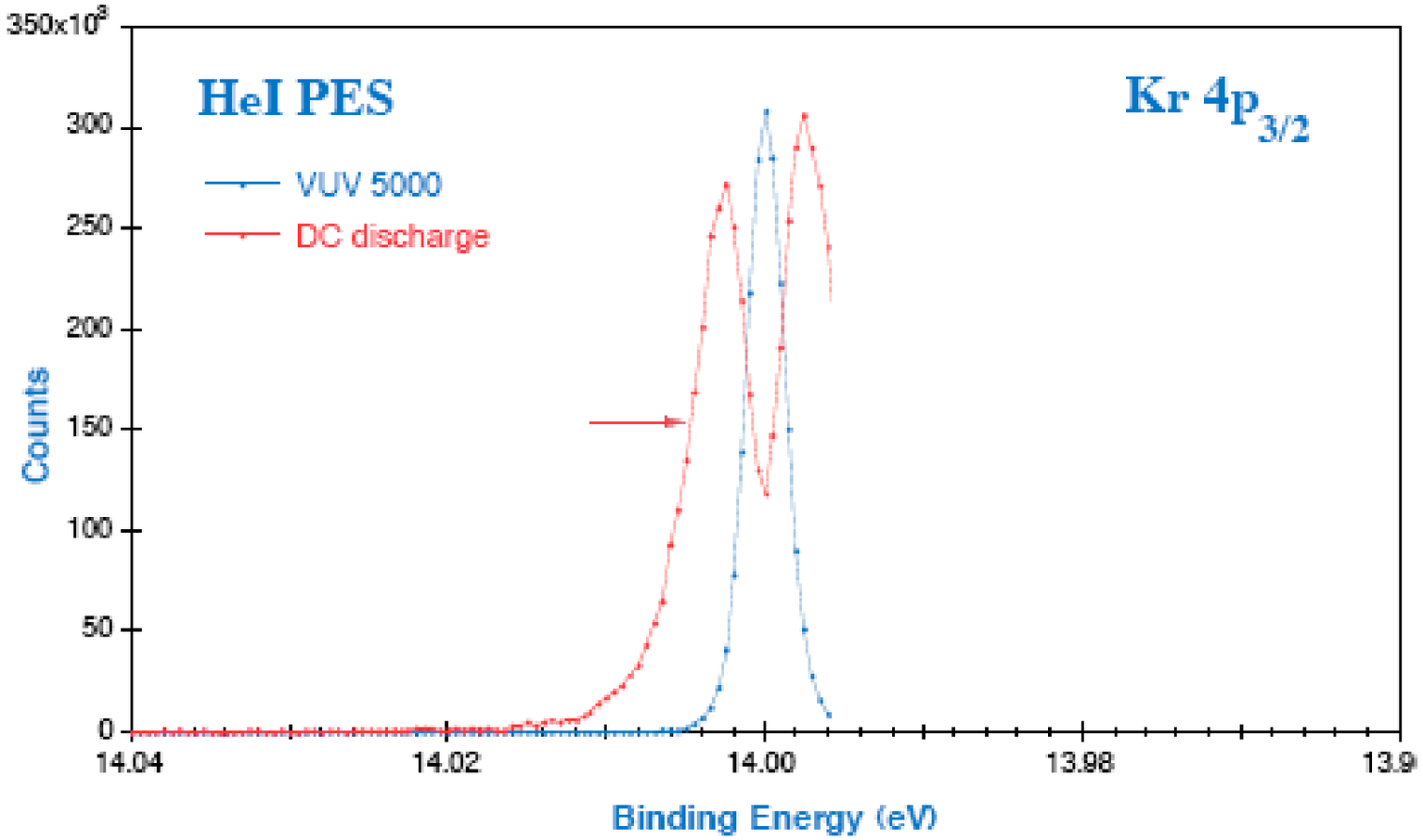
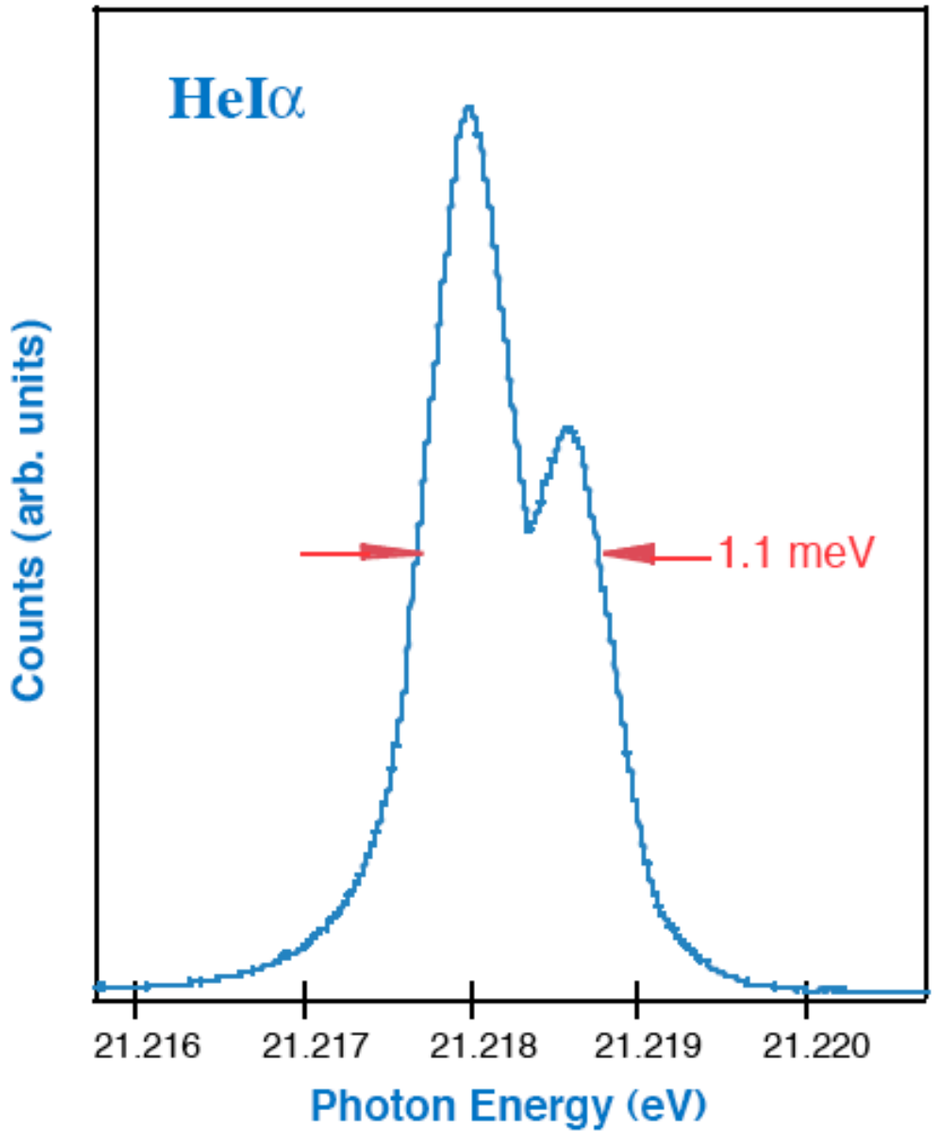
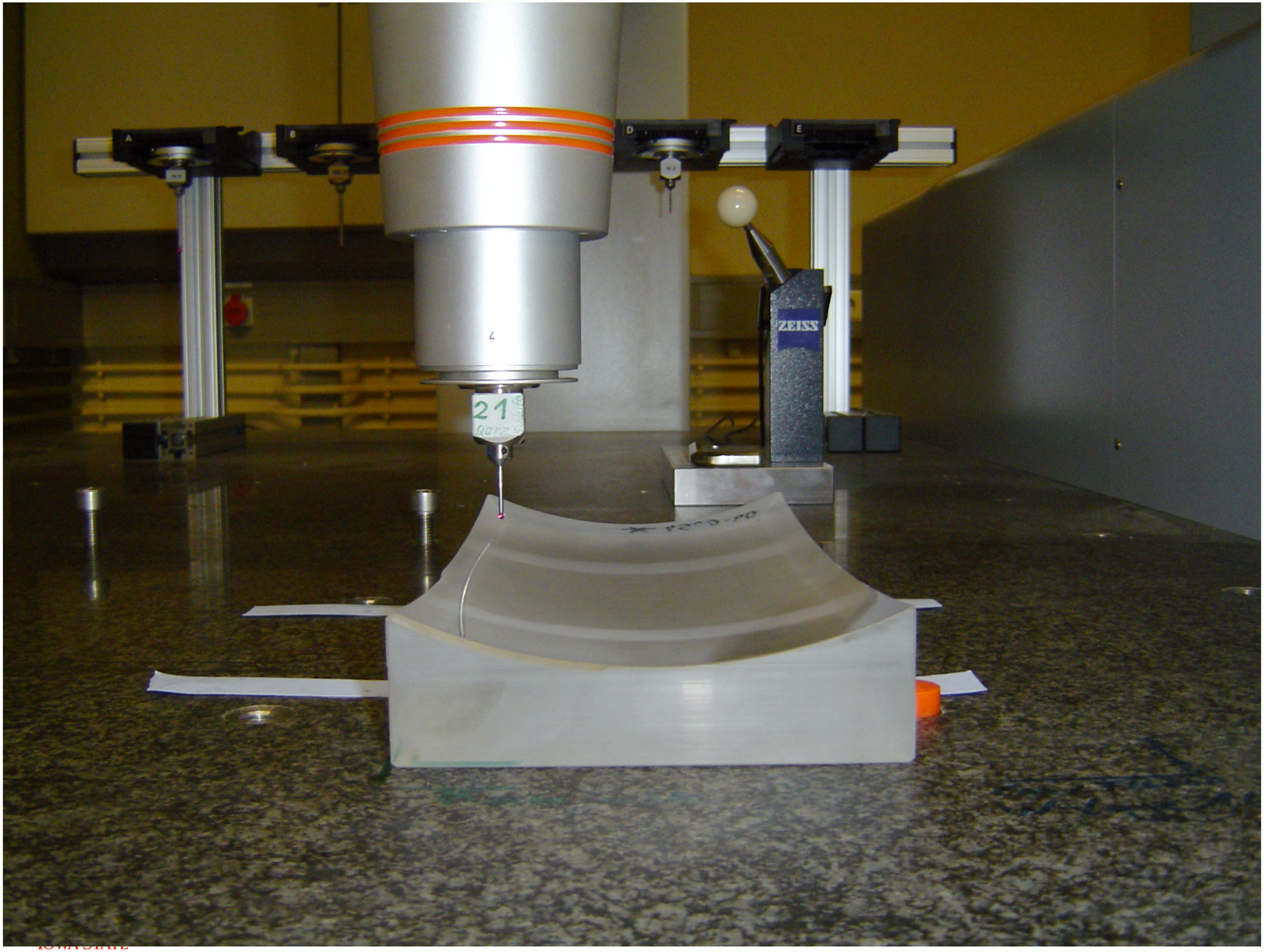
Comparison with traditional DC discharge lamps






A
B
D
E
ZEISS
21
Qartz

New alternative source: UV laser

Laser

Photon energy: 6.994 eV

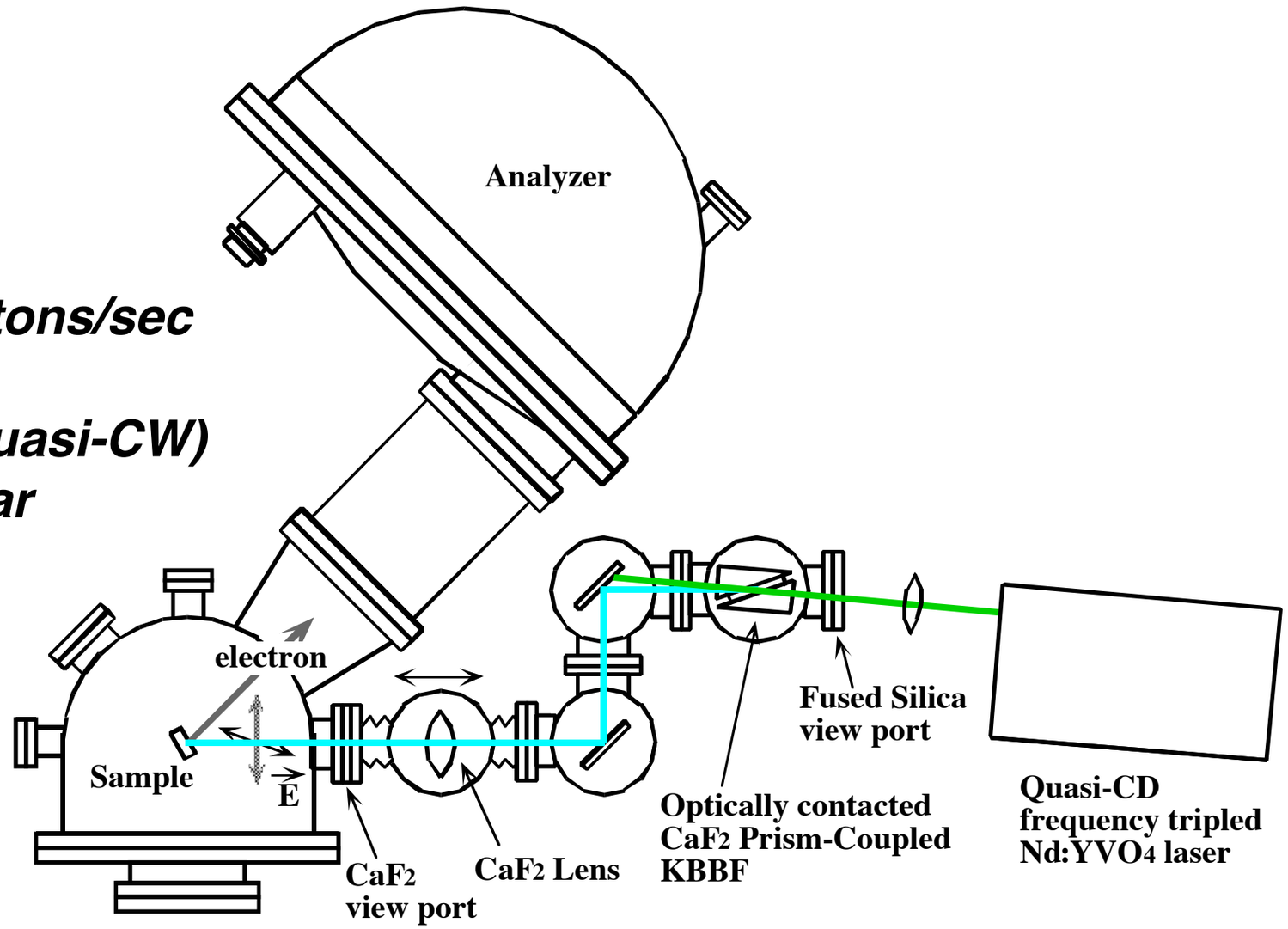
FWHM=0.26 meV

Photon flux: 2.2x10^{15} photons/sec

Spot size: 0.2 μm

Repetition Rate:80MHz(Quasi-CW)

Polarization: linear,circular



Yokoya et al.

ARPES Lab of Prof. S. Shin

Institute for Solid State Physics (ISSP), University of Tokyo

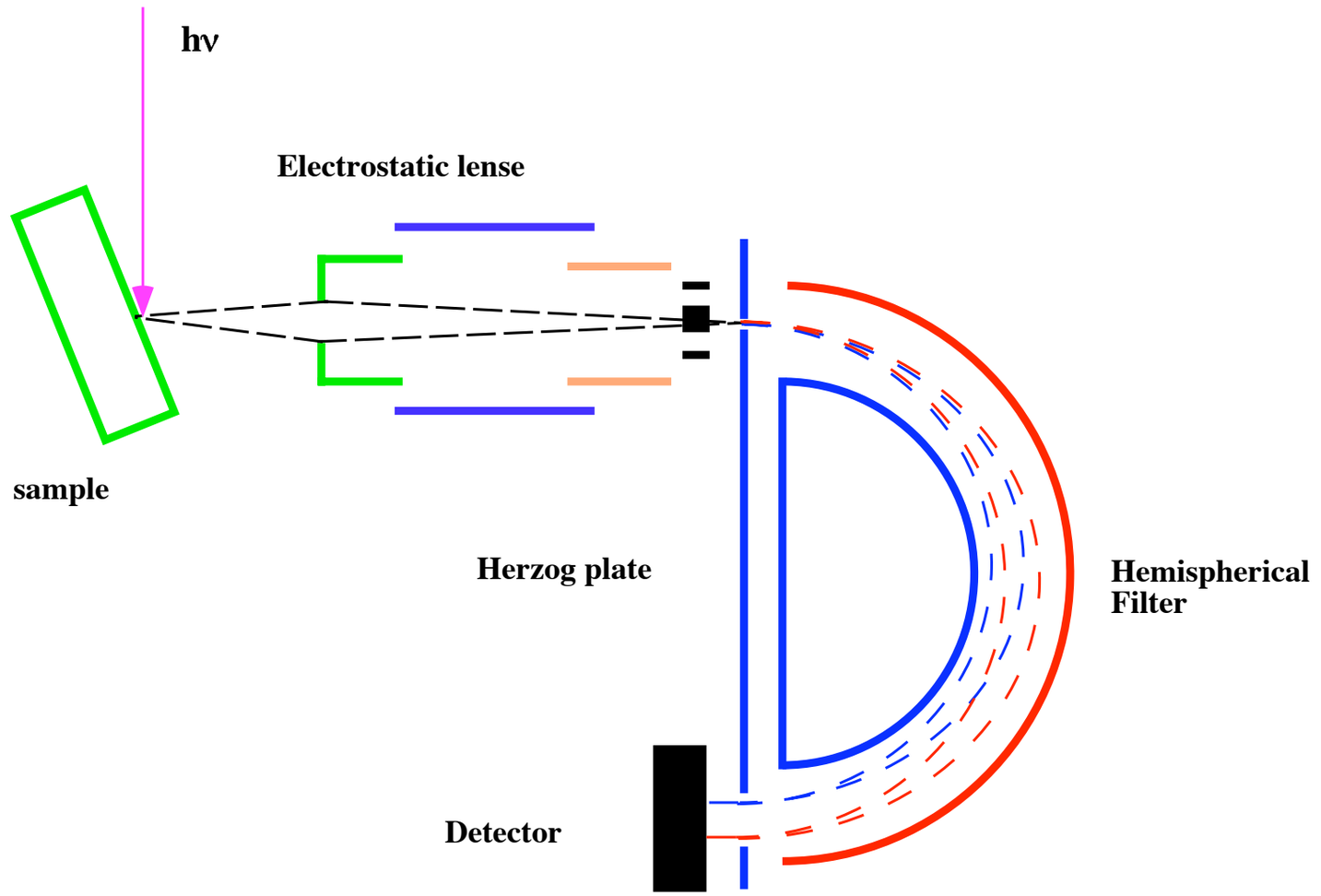
Electron analyzers

Energy range: 7 eV - 1000 eV

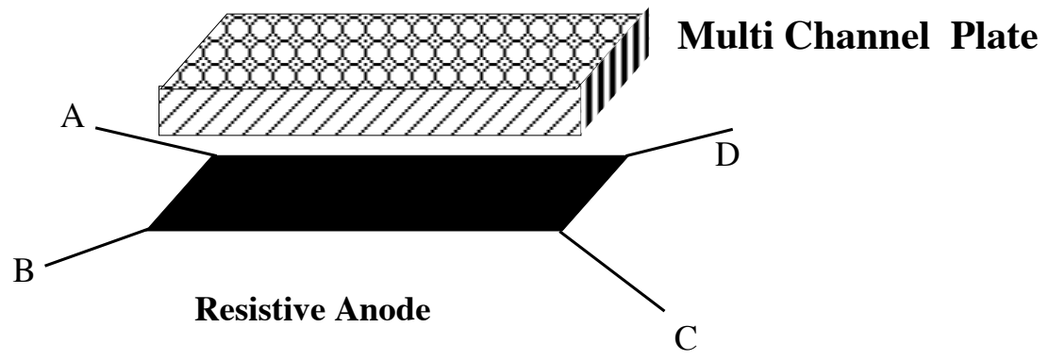
Energy resolution 1-30 meV

Momentum resolution 0.1 deg (1/400 of BZ)

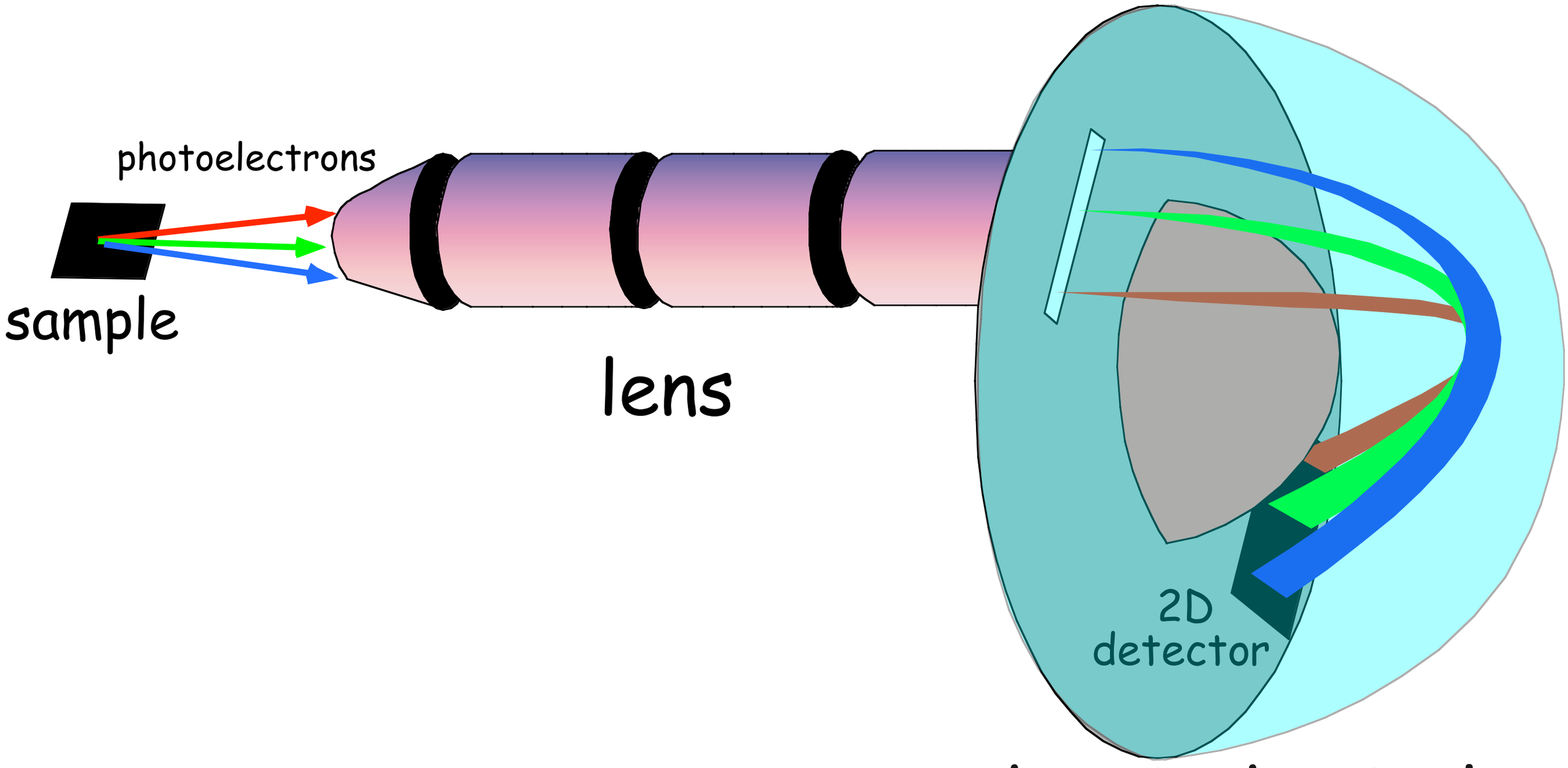
Single channel/multichannel



Position Sensitive Detector

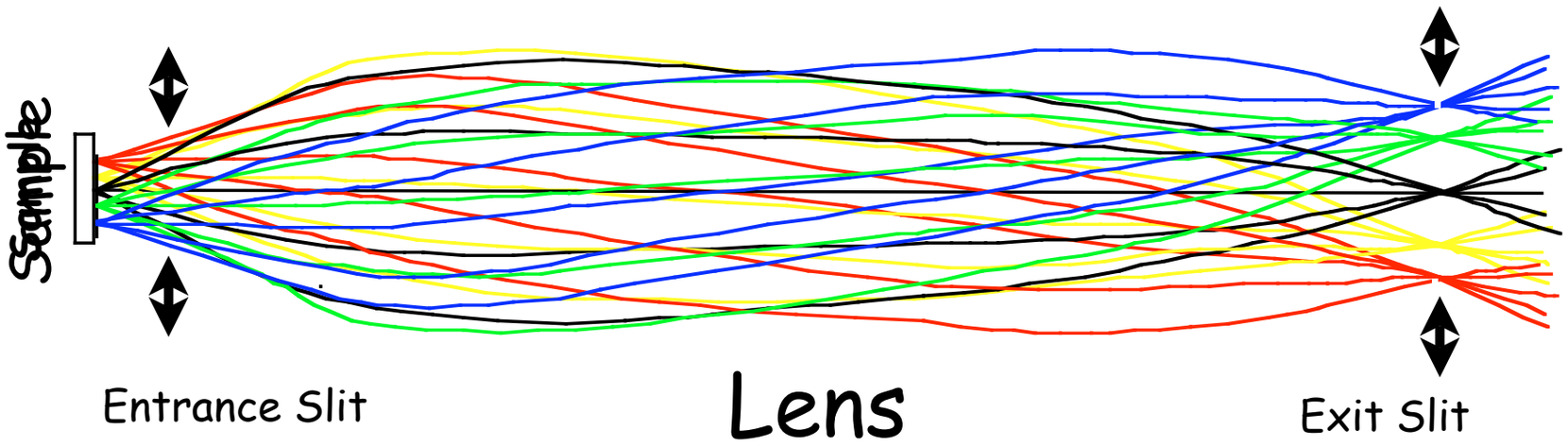


Electron analyzer

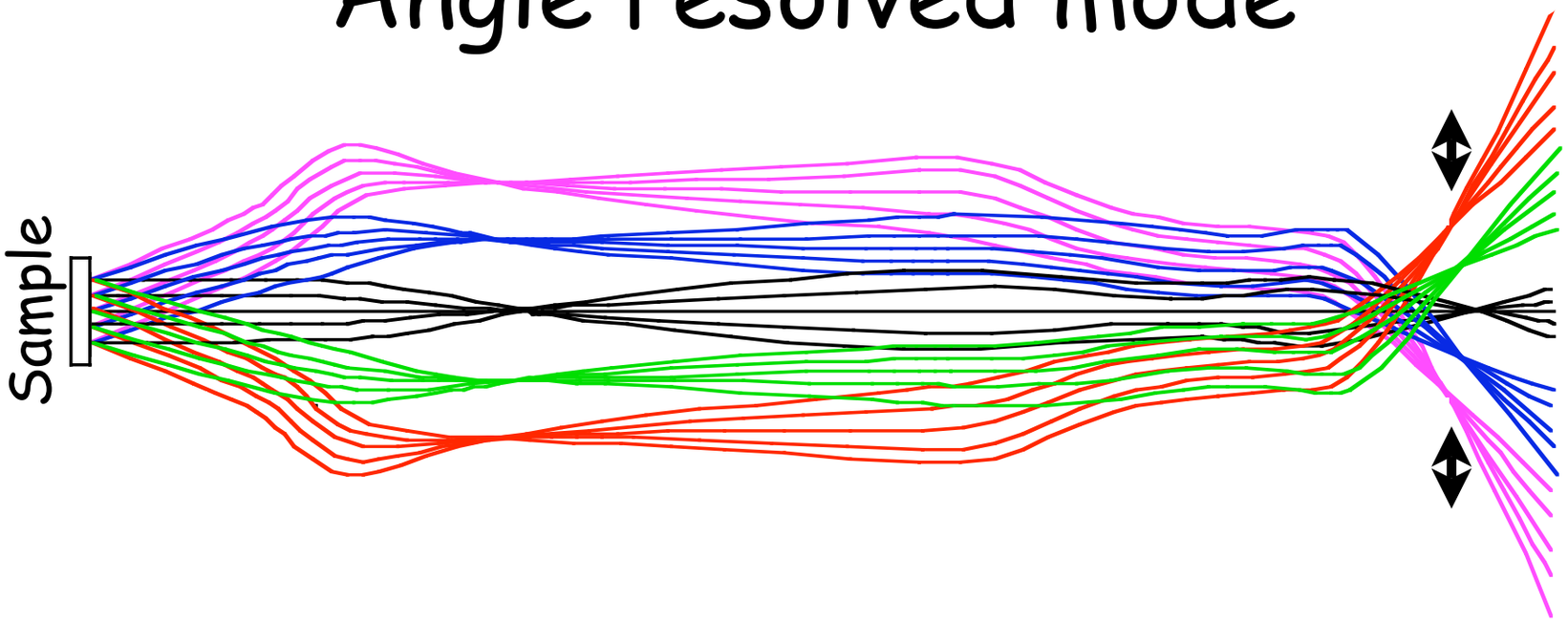


hemispherical
analyzer

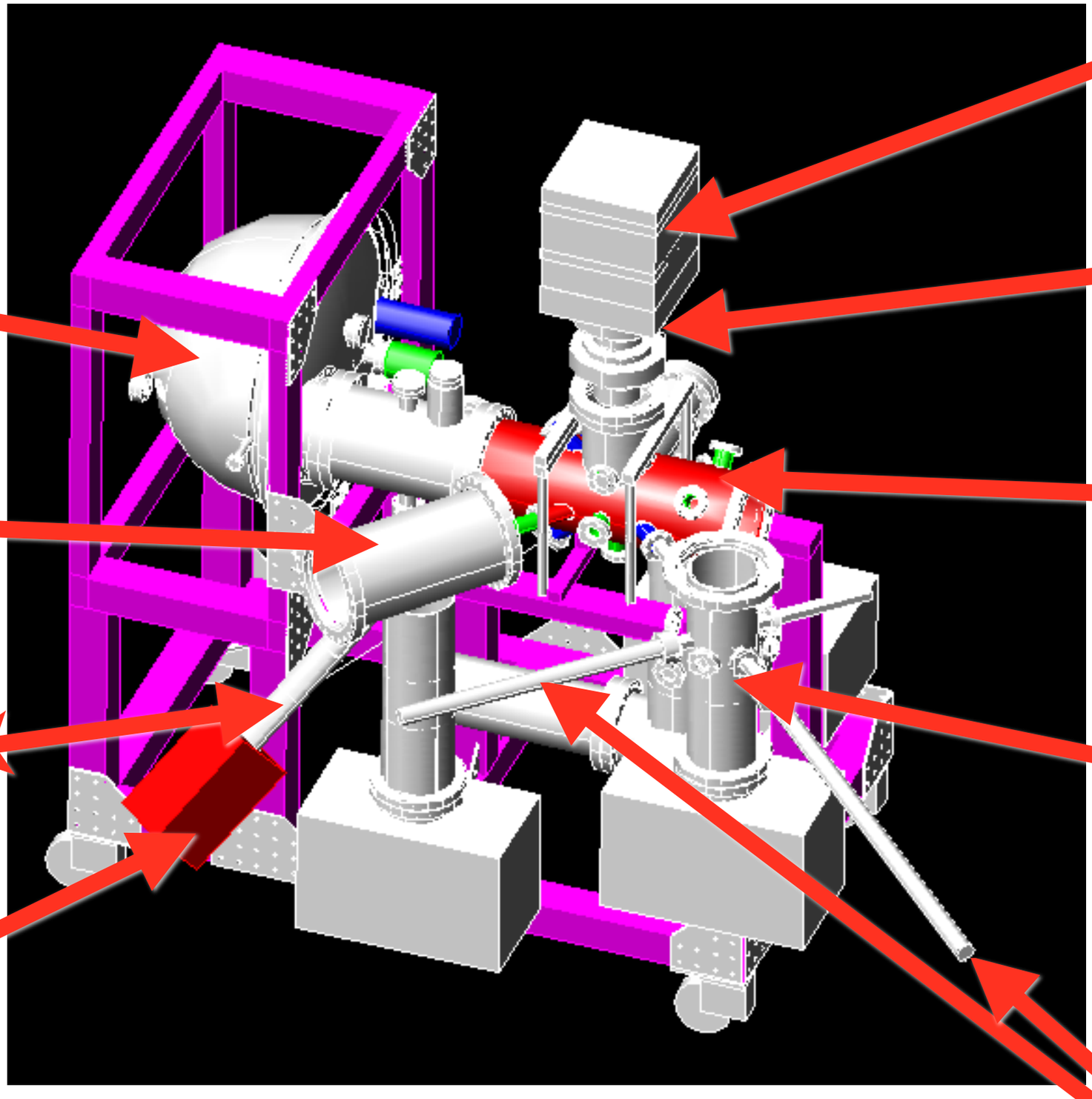
Transmission mode



Angle resolved mode



Laboratory based ARPES



displex refrigerator

SES2002 analyzer

sample manipulator

refocusing mirror

μmetal chamber

microcapillary

preparation chamber

UV source

transfer manipulators

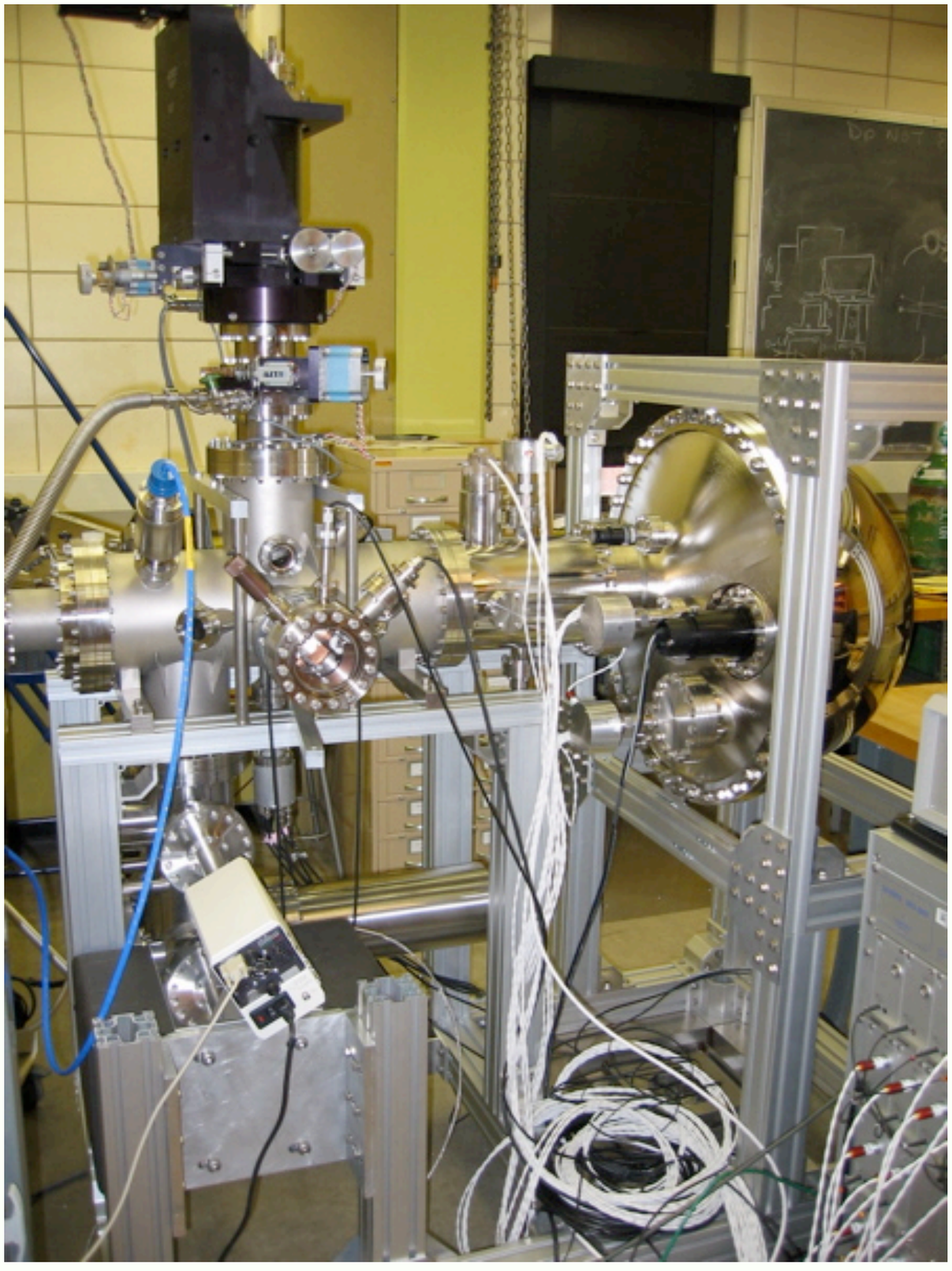
… high precision lab-based ARPES system

Energy resolution:
~1 meV

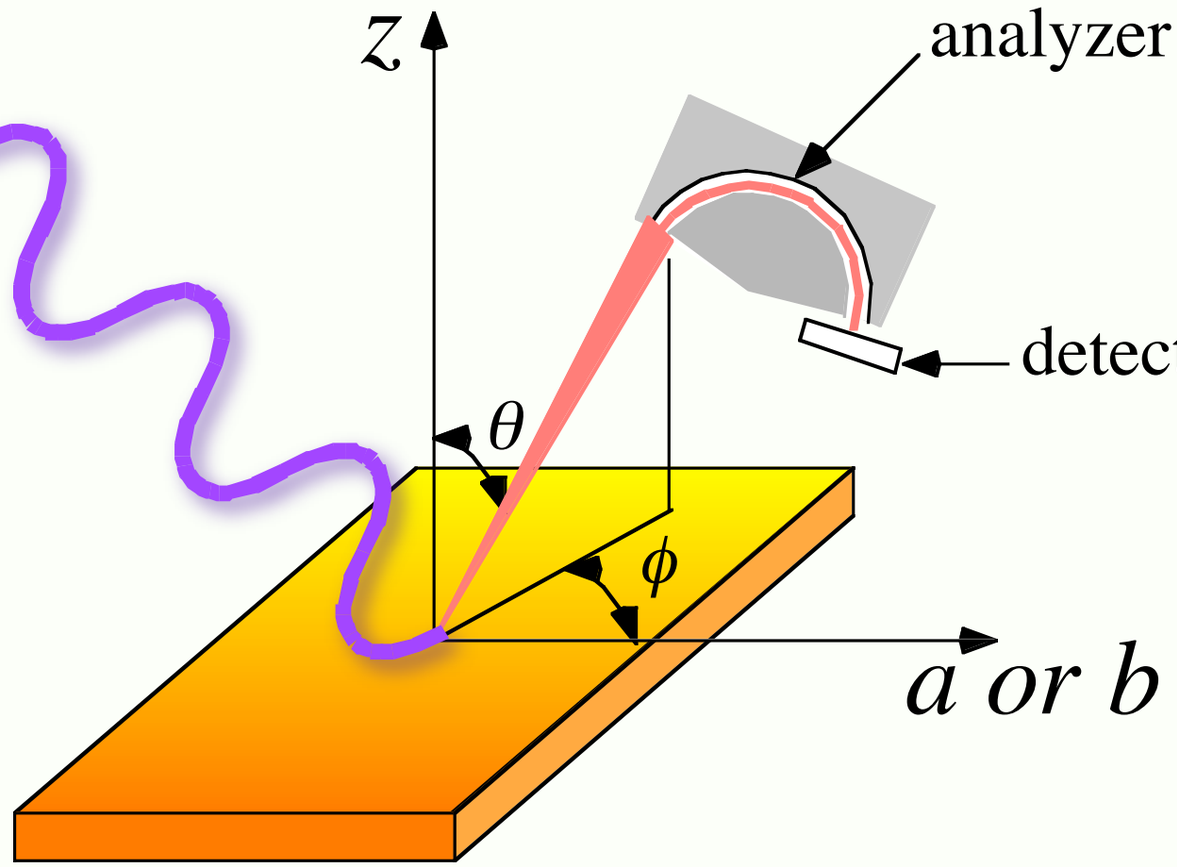
Angular resolution:
0.1 deg.

UV source:
10^{13} photons/sec.

Sample positioning:
~1μm



ARPES experiment



We need:

binding energy - E_b

initial momentum - k^i

$$E_b = E - h\nu + W$$

$$k^i_{||} = k^f_{||} = \sqrt{2mE/\hbar^2}\,\sin\theta$$

$$k^i_{\perp} = k^f_{\perp} - G = \sqrt{2mE/\hbar^2}\,\cos\theta - G$$

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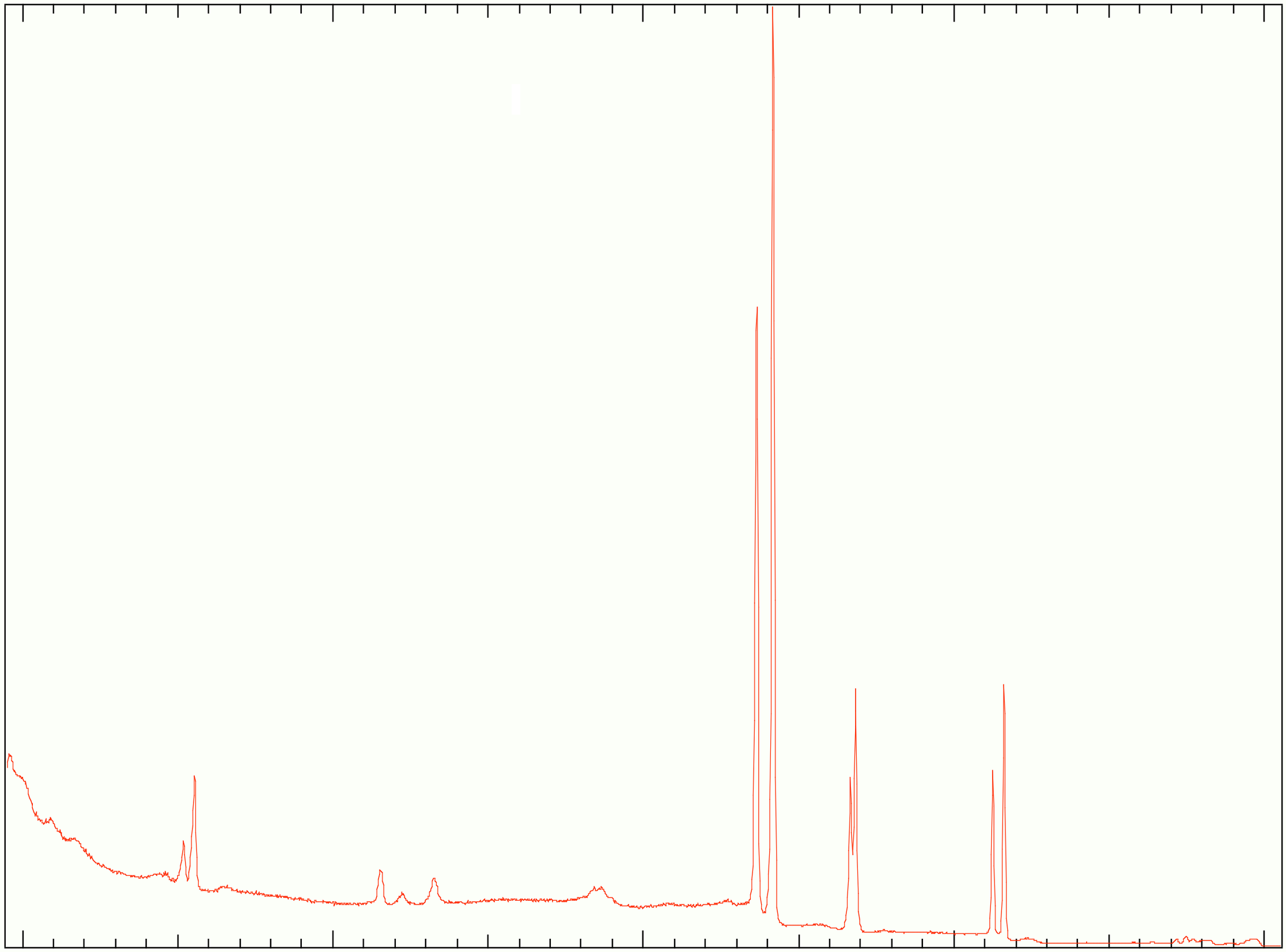
typical photoemission spectrum from Bi2212



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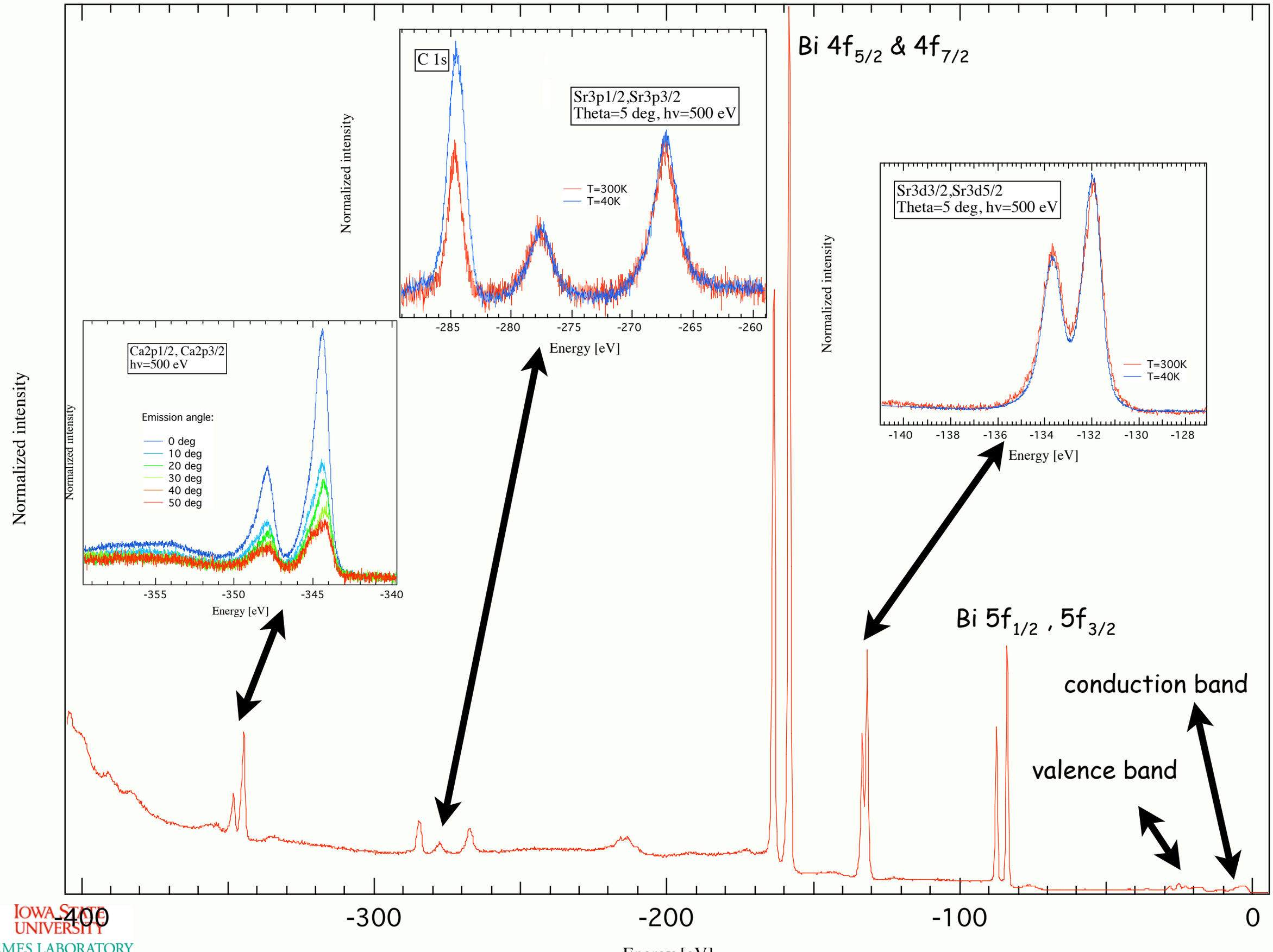
typical photoemission spectrum from Bi2212



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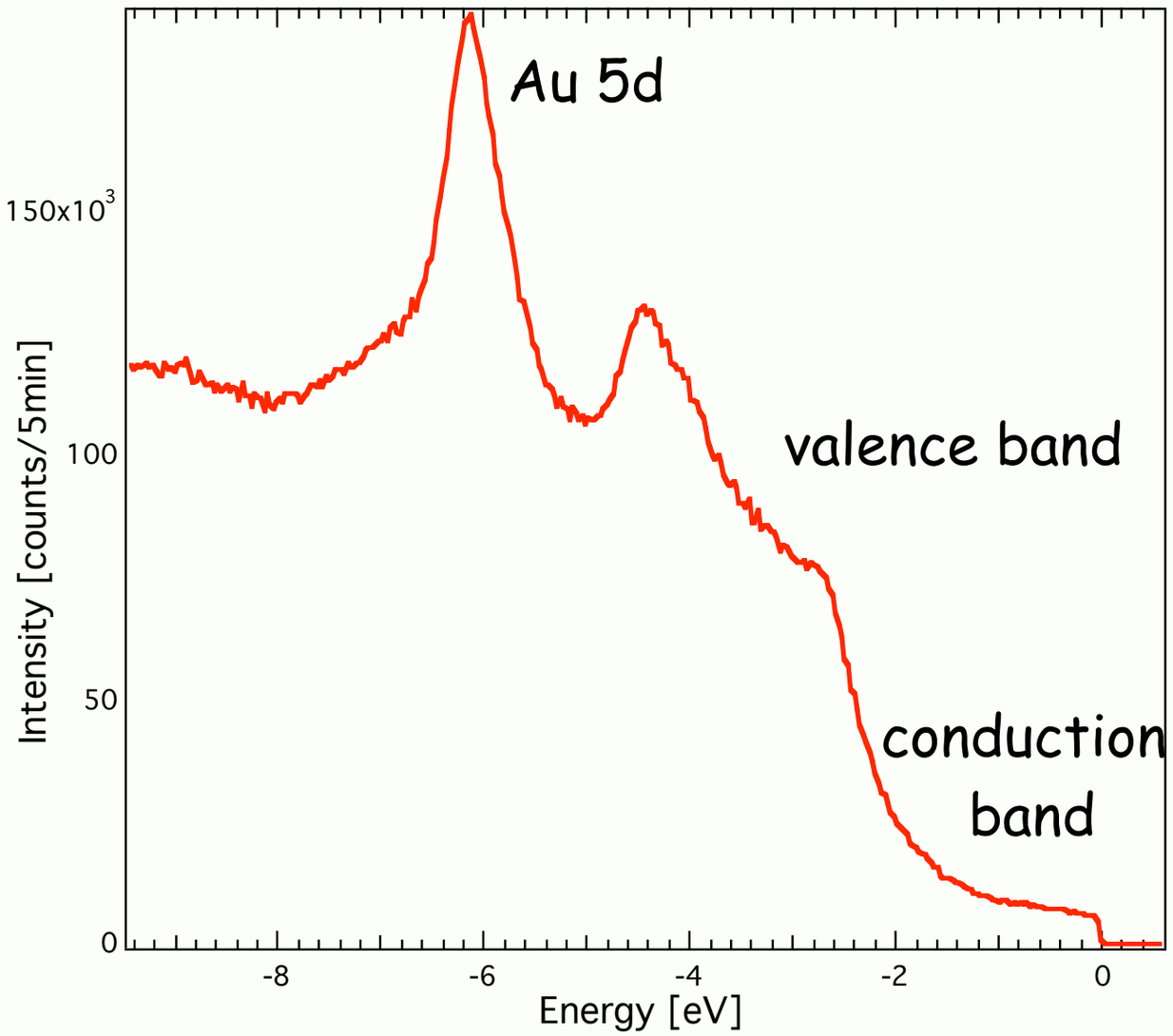
Valence and conduction bands - simplest example: poly Au



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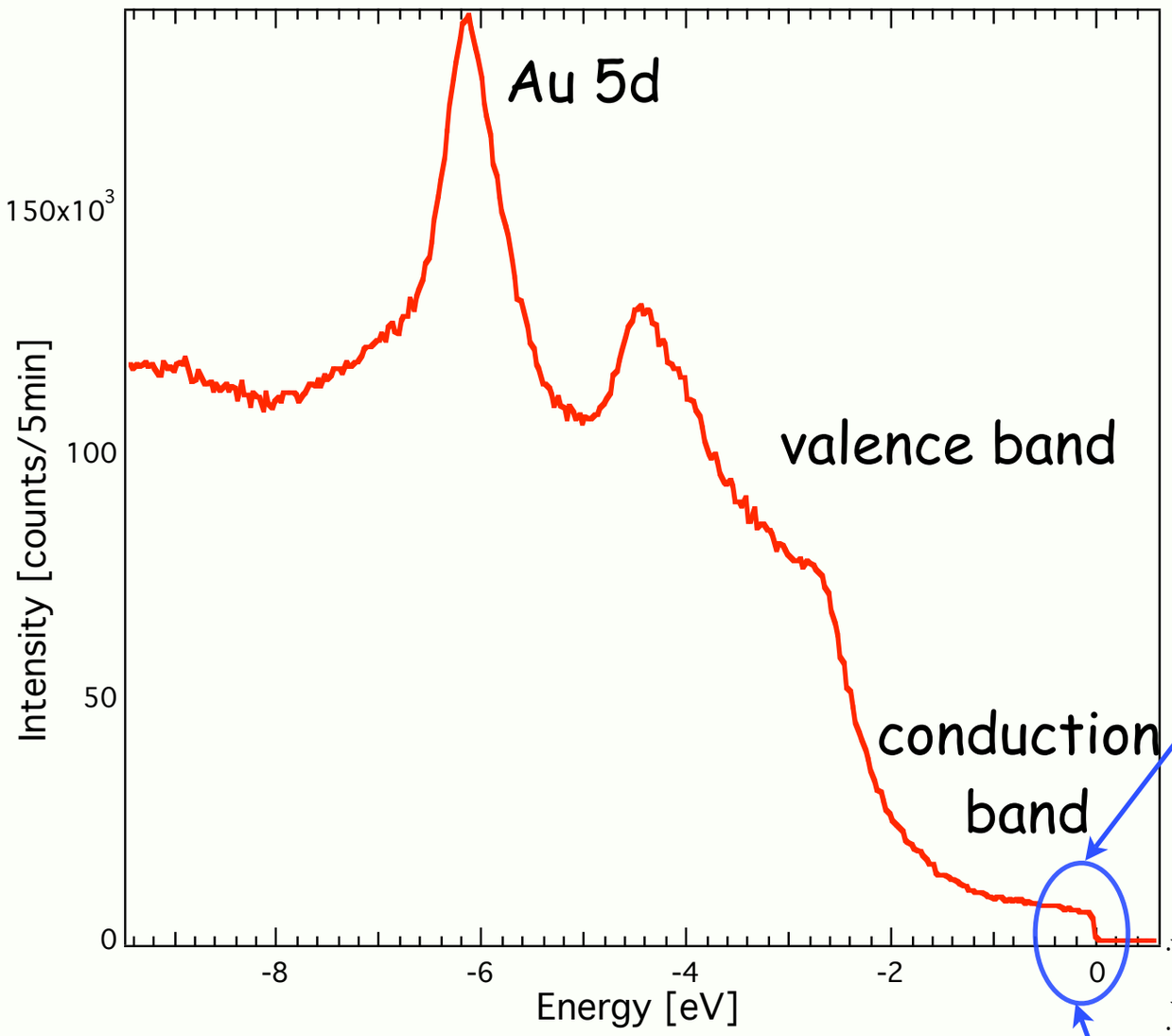

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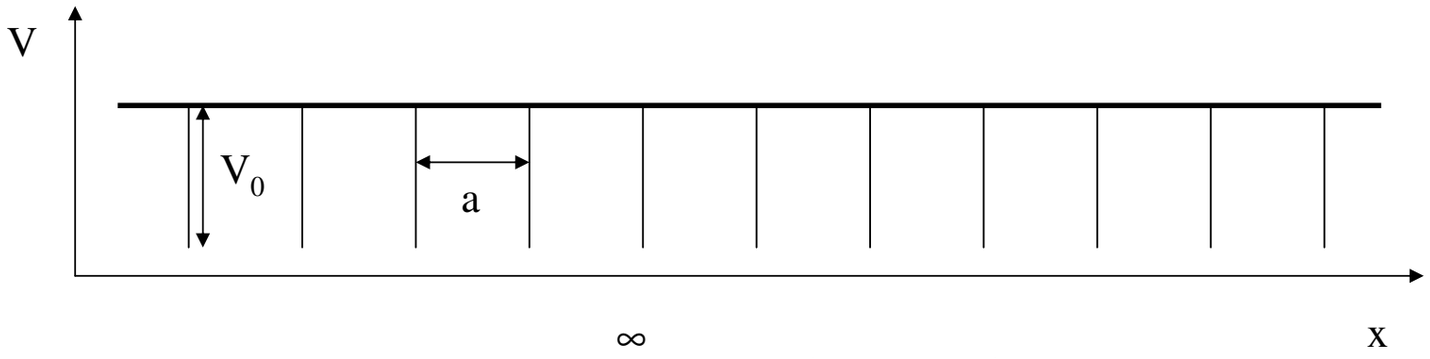
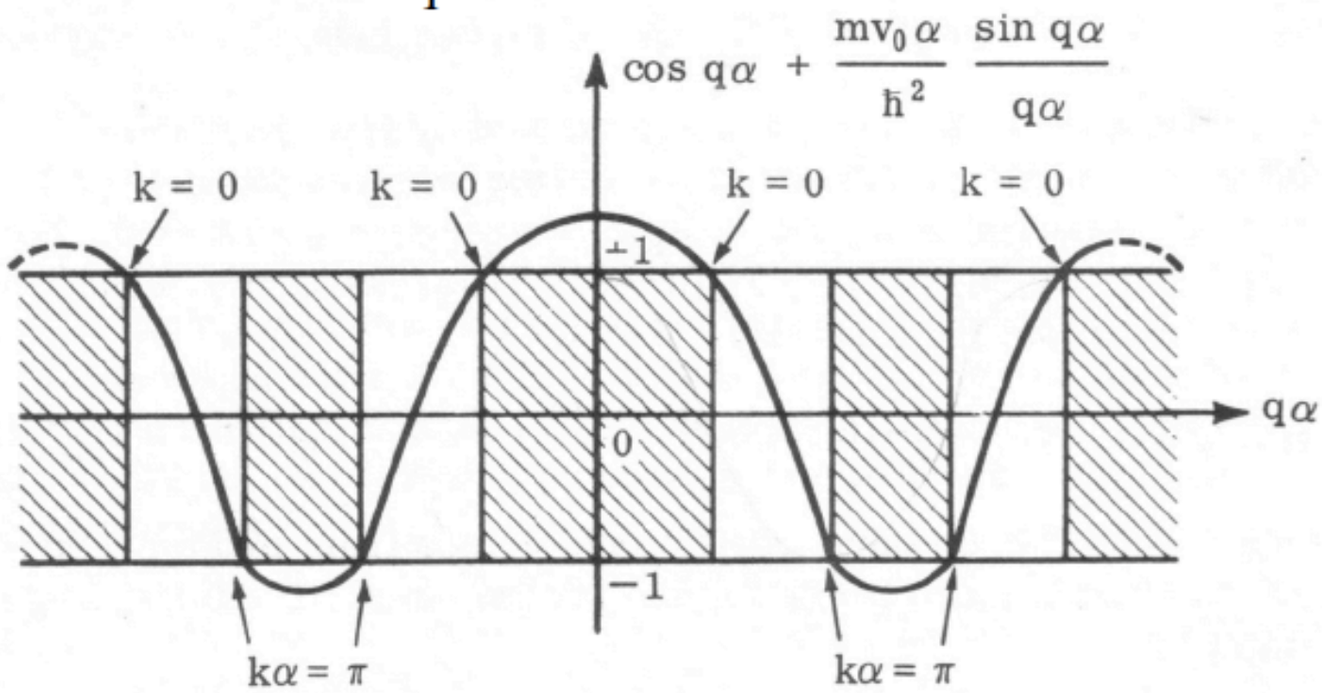
The Krönig-Penney model:

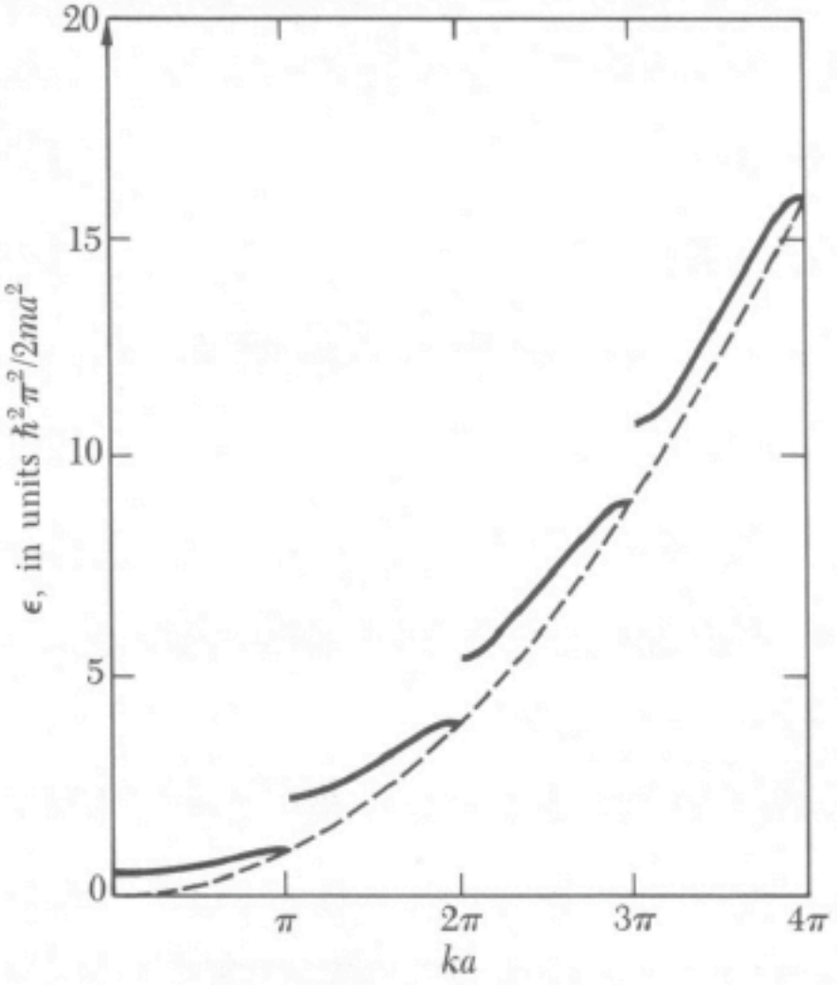


$$V = \sum_{-\infty}^{\infty} V_0 \delta(x - na)$$

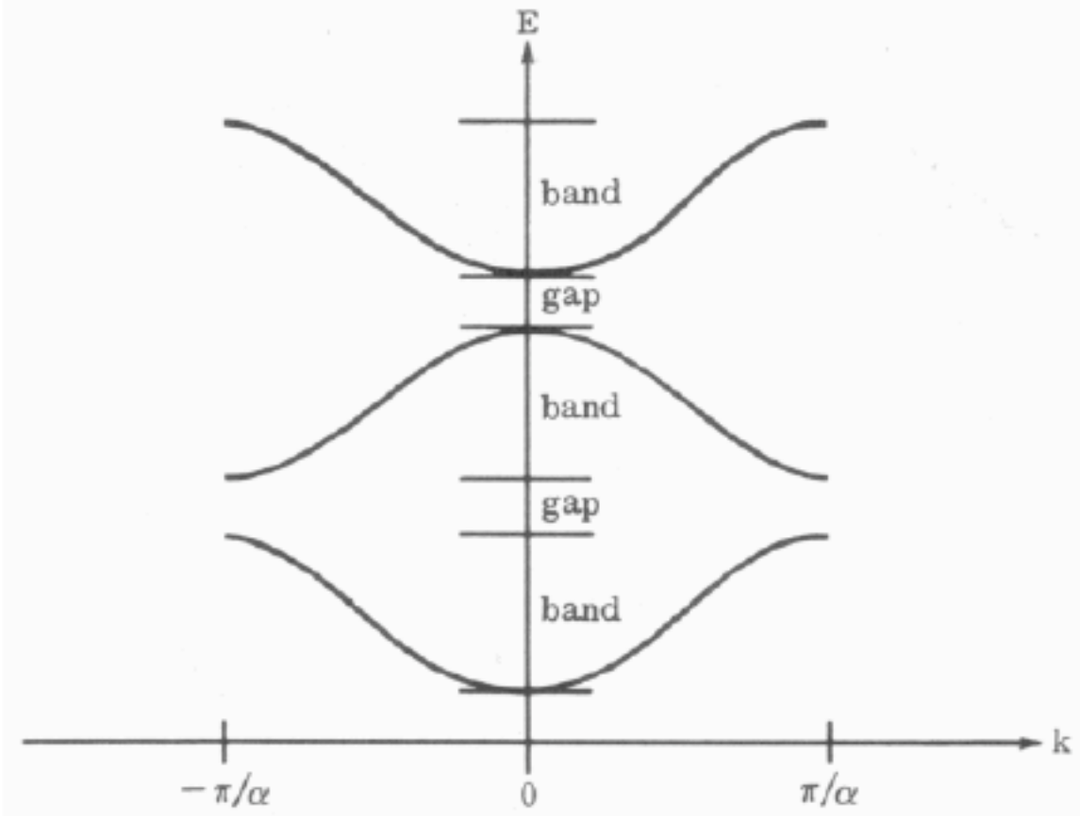
$$\left(E + \frac{\hbar^2}{2m} \frac{d^2}{dx^2} \right) \psi(x) = \sum_{-\infty}^{\infty} V_0 \delta(x - na) \psi(x)$$

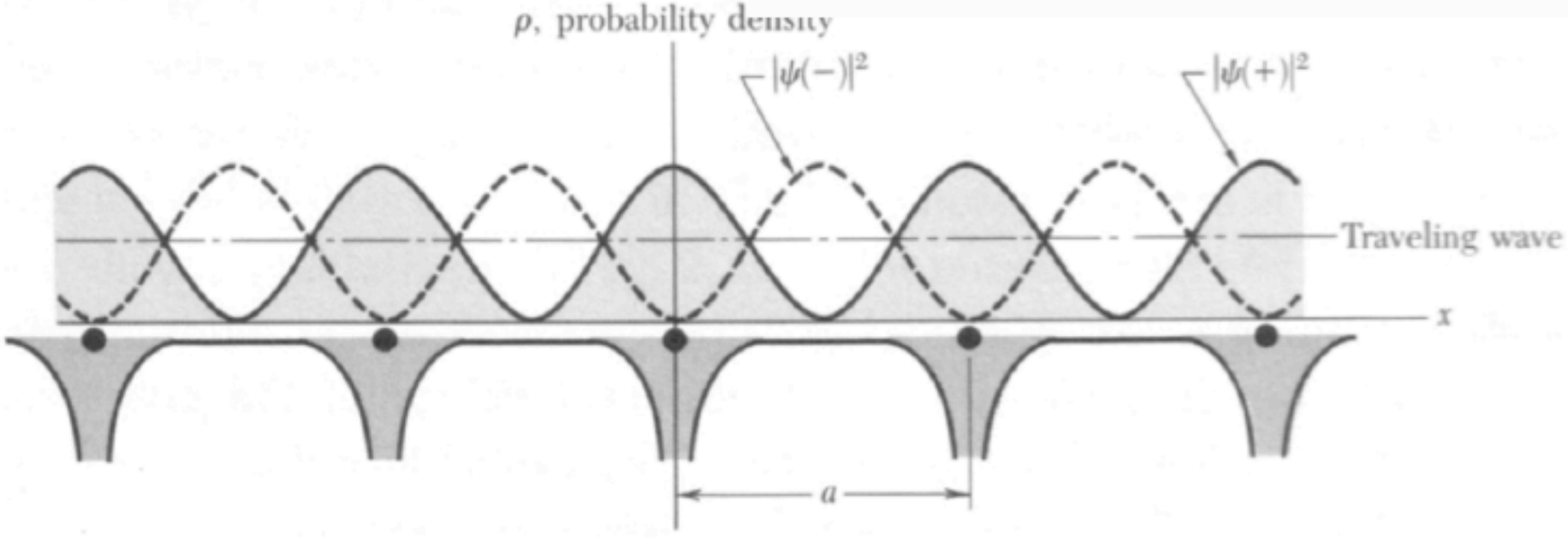
Thus: $\cos ka = \cos qa + \frac{mV_0 a}{\hbar^2} \frac{\sin qa}{qa}$



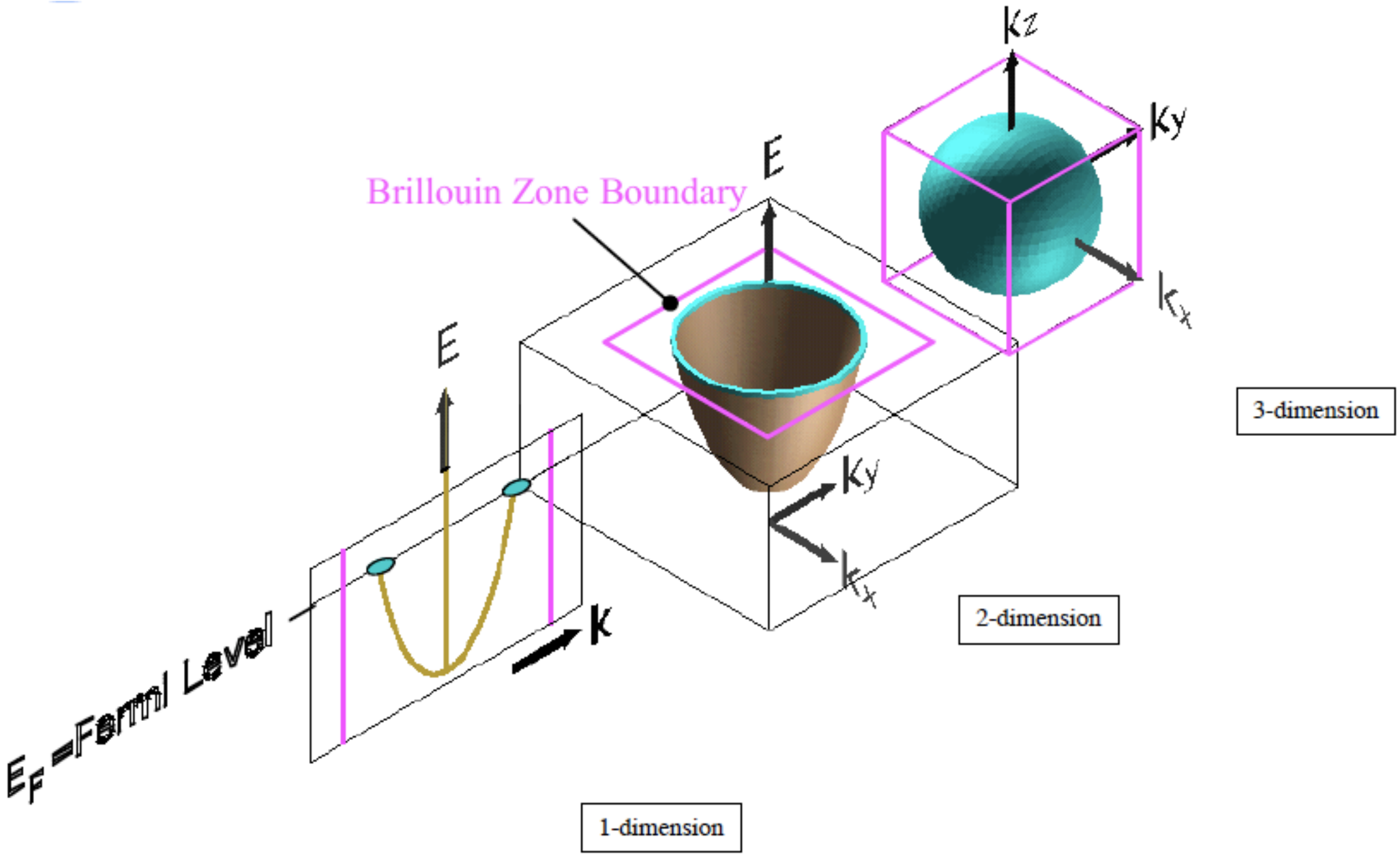


Reduced band scheme



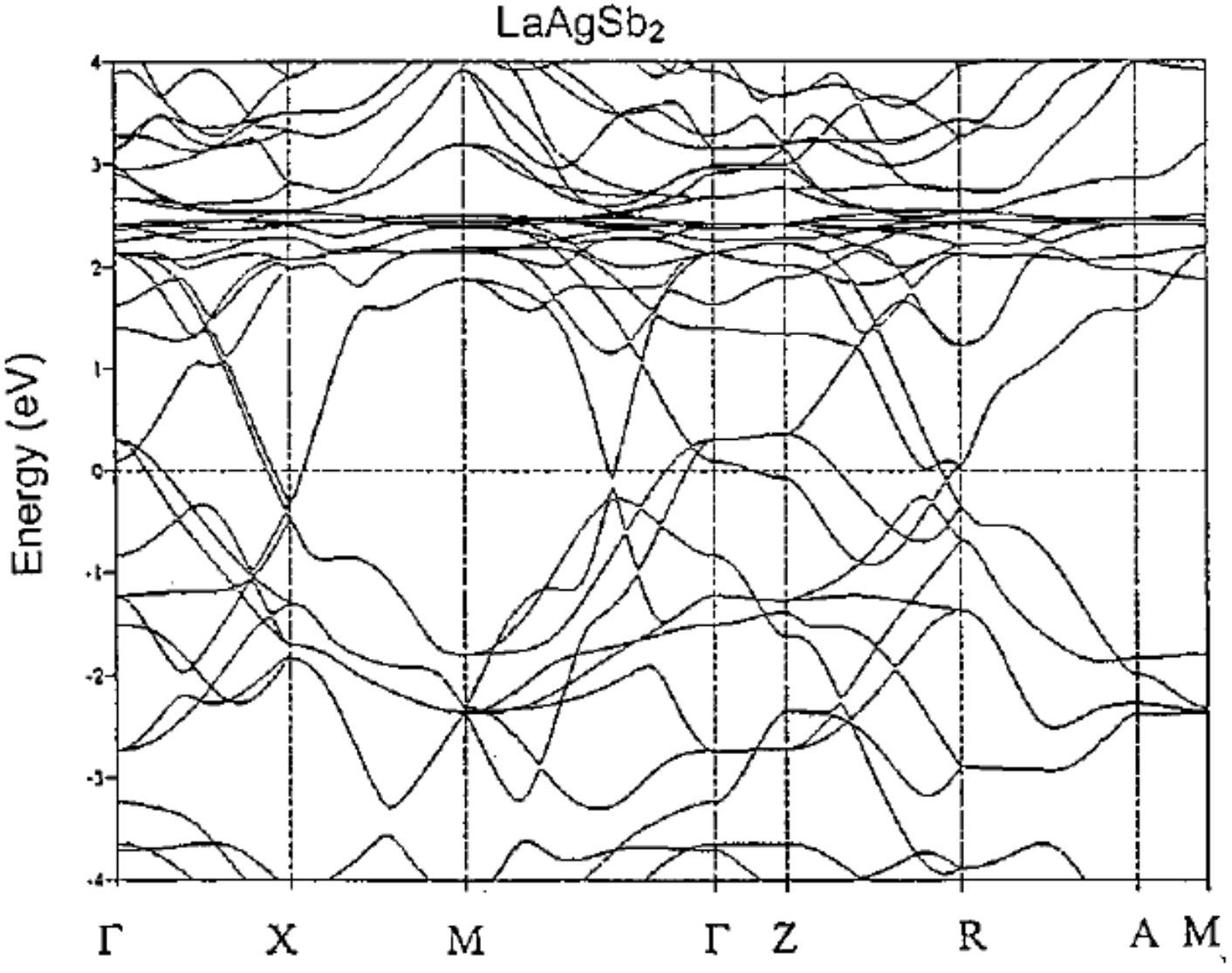


Fermi surface

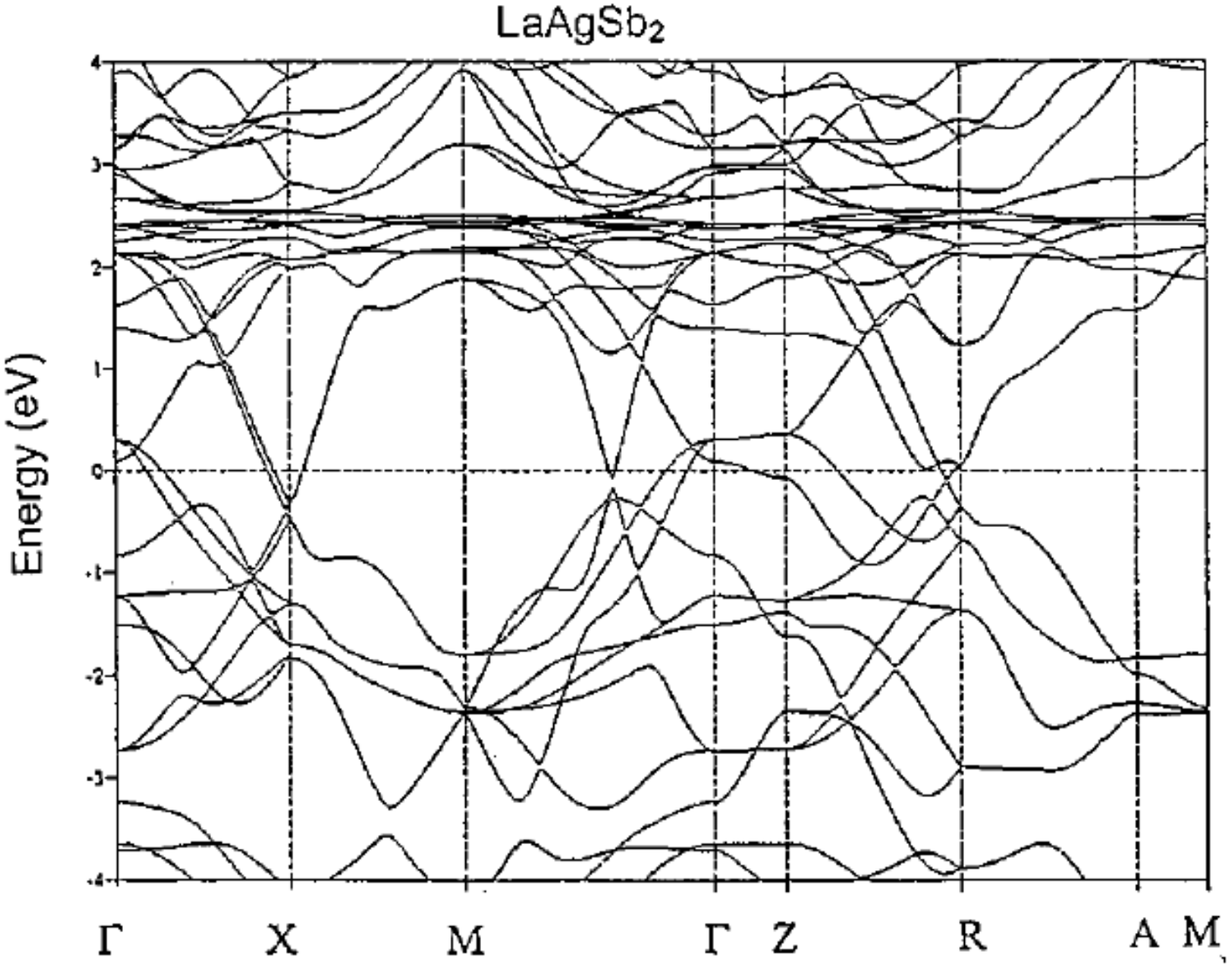


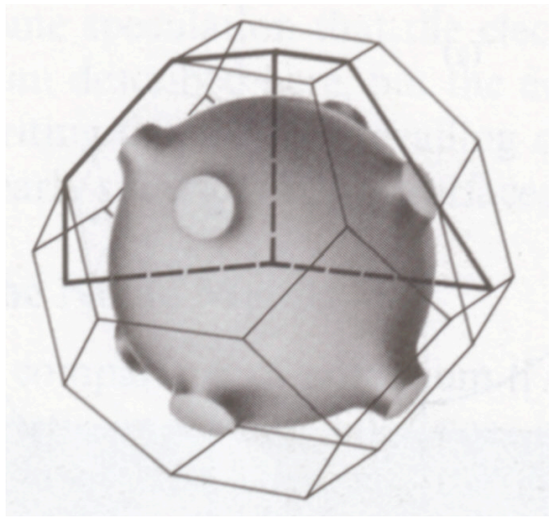
E. Rotenberg, Berkeley-Stanford Summer School 2001

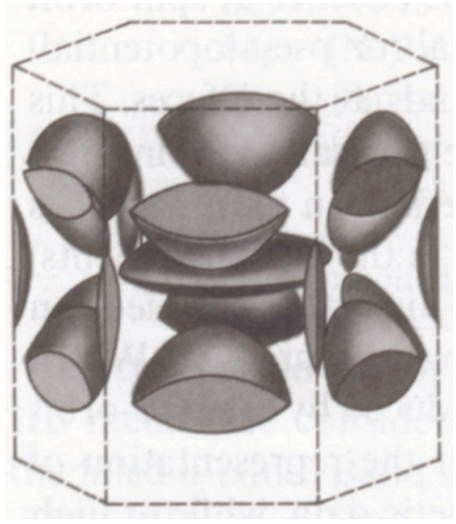
Band structure and Fermi surface - real world

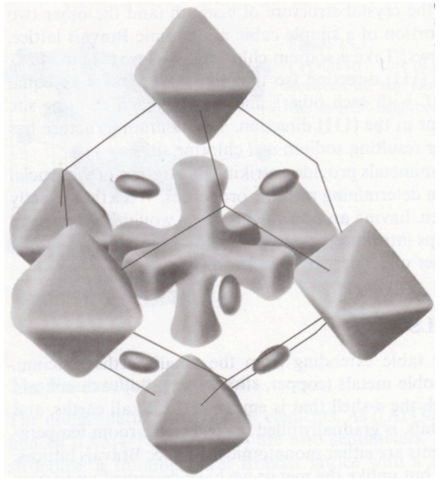


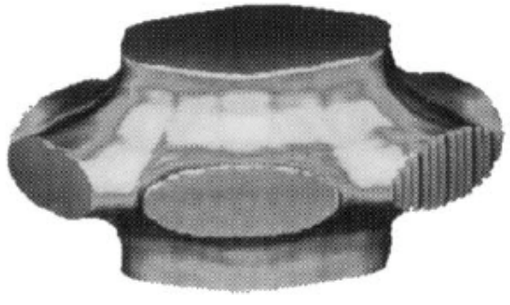
Band structure and Fermi surface - real world



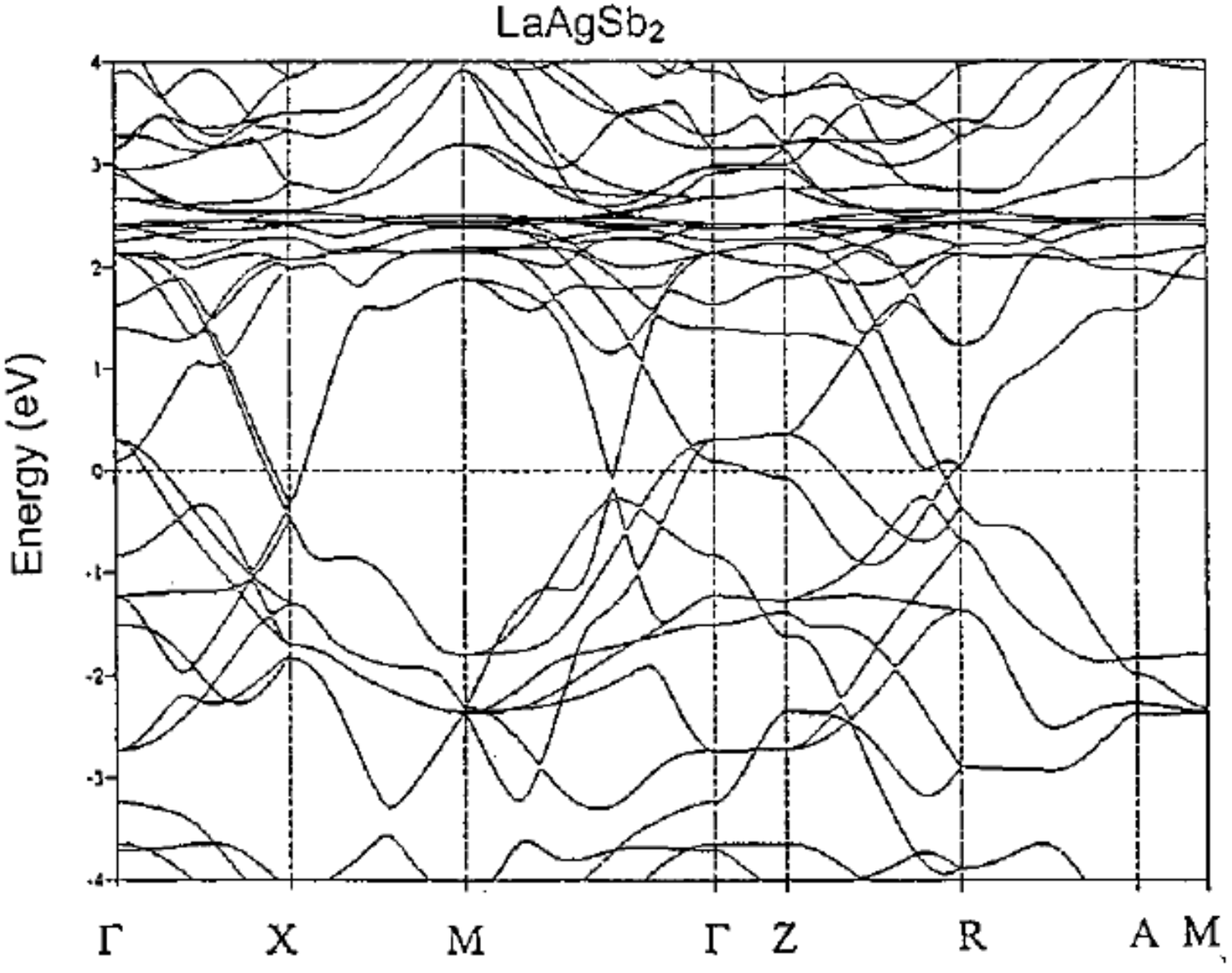


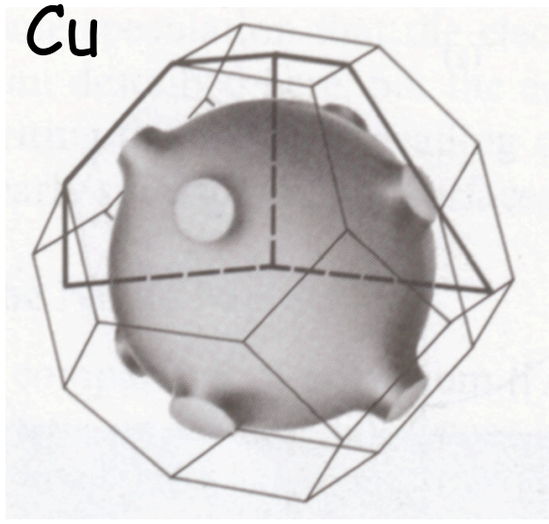


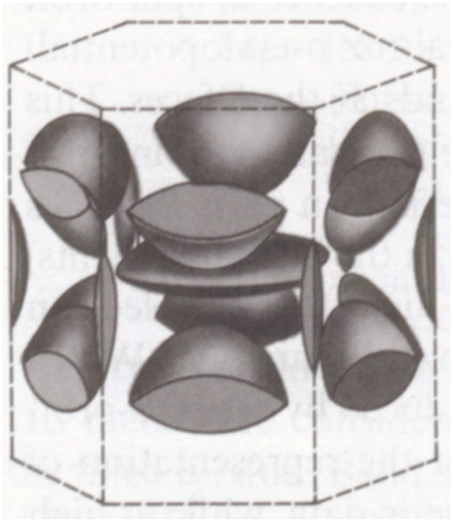


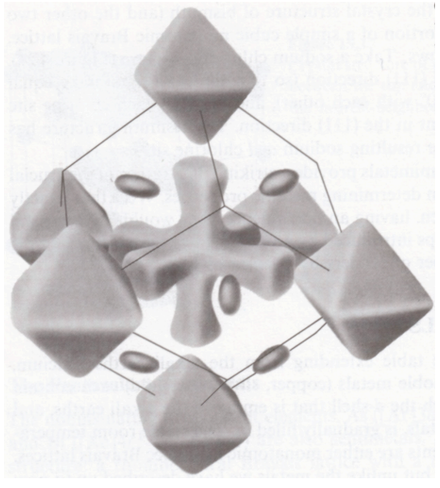


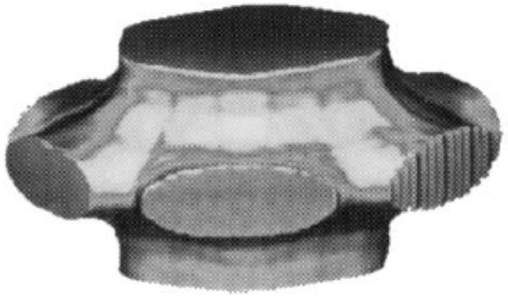
Band structure and Fermi surface - real world



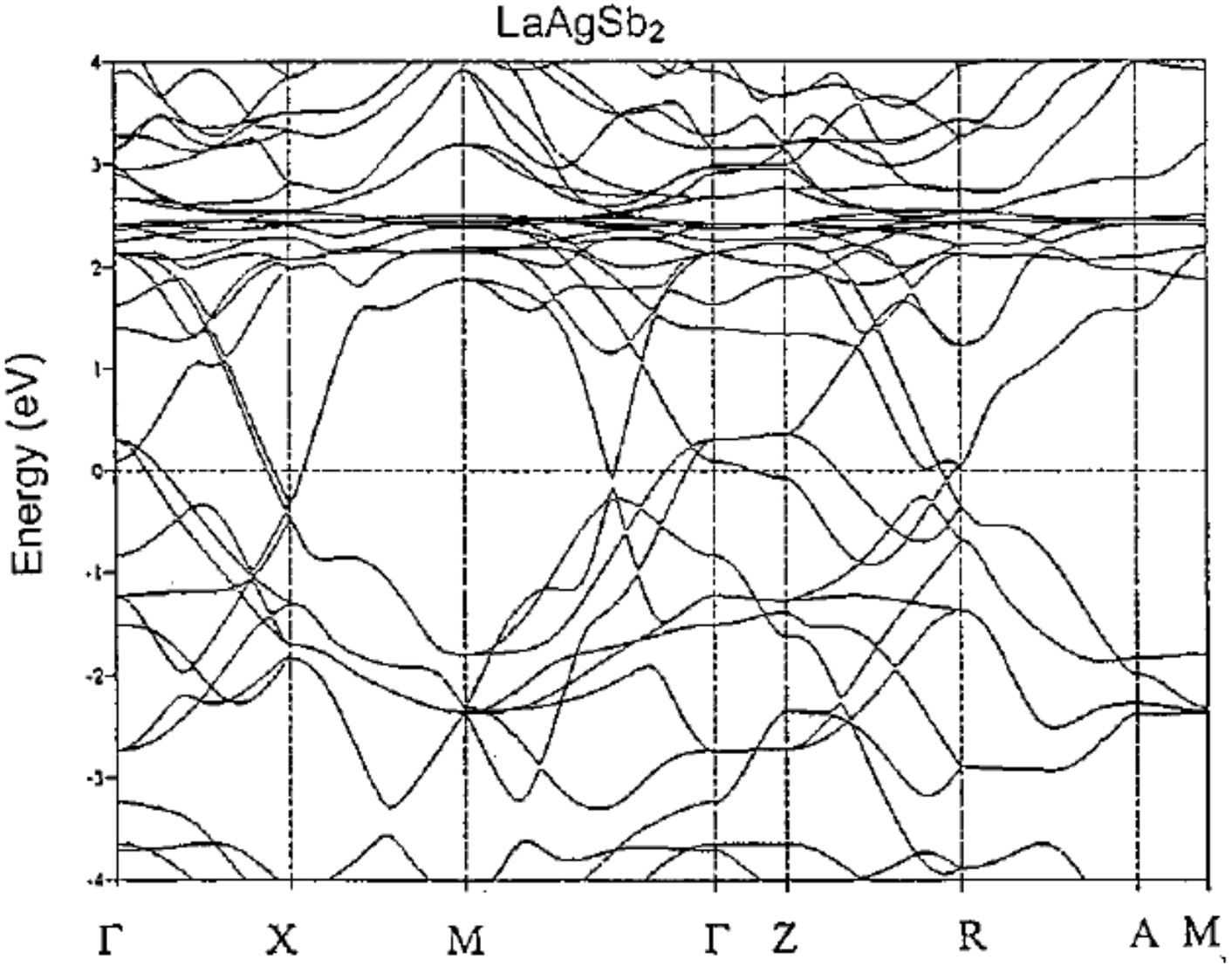


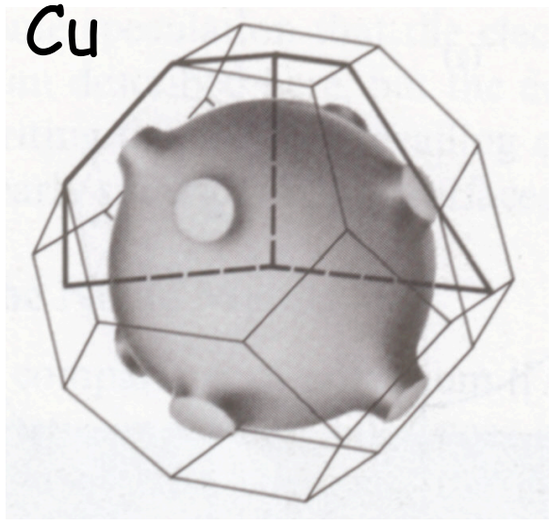


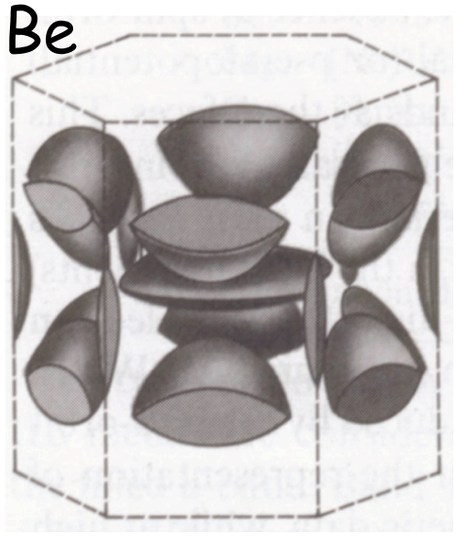


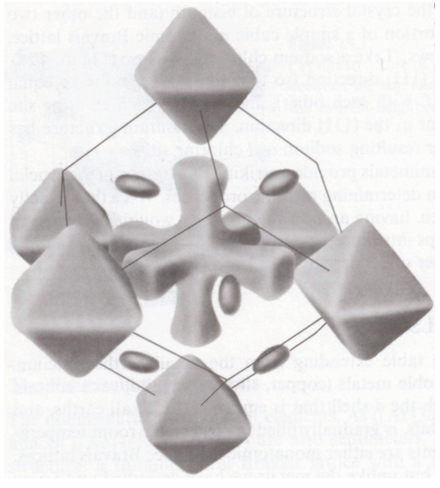


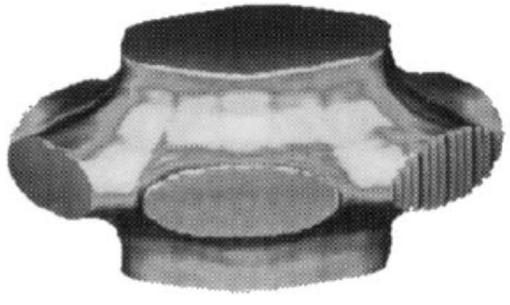
Band structure and Fermi surface - real world



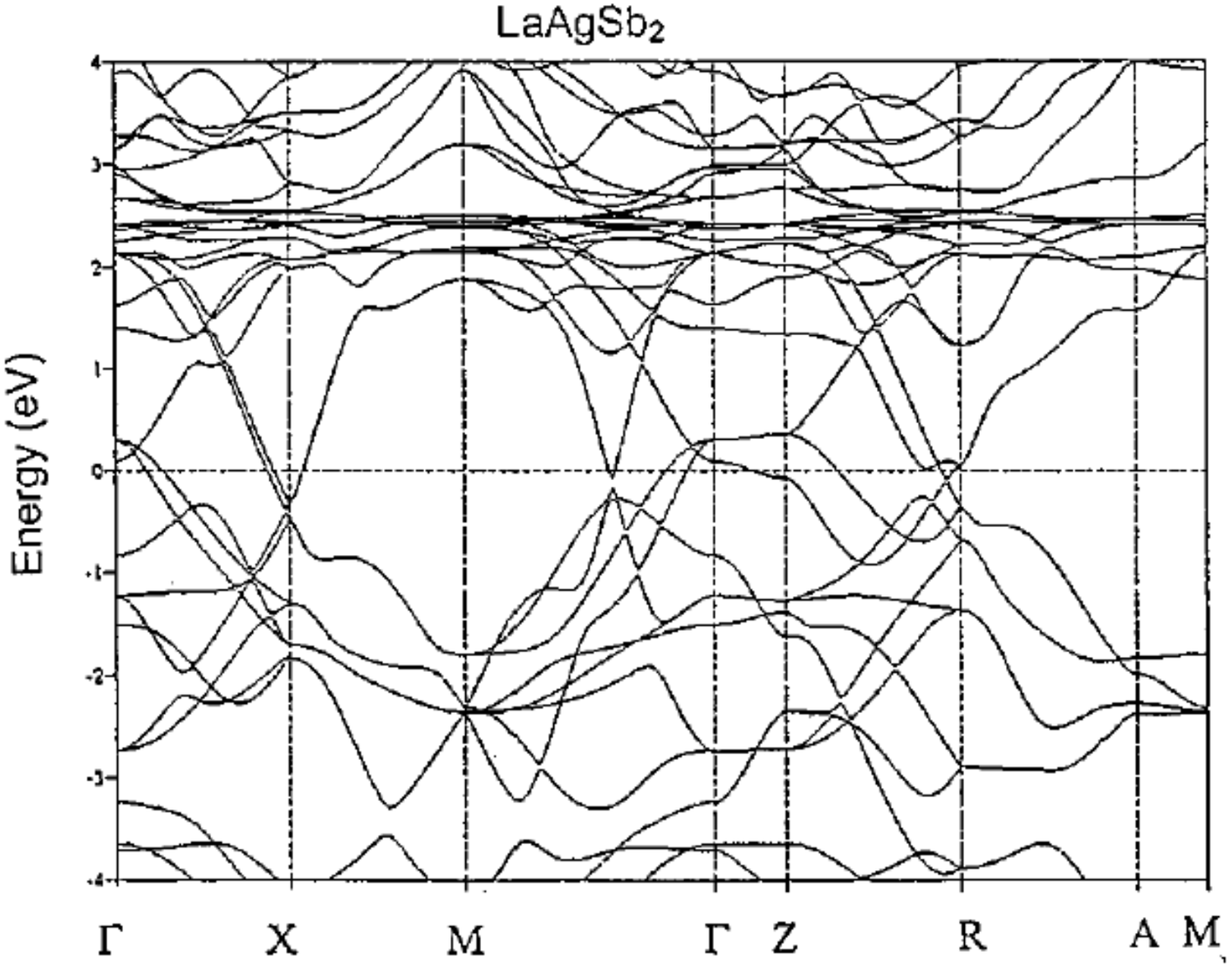


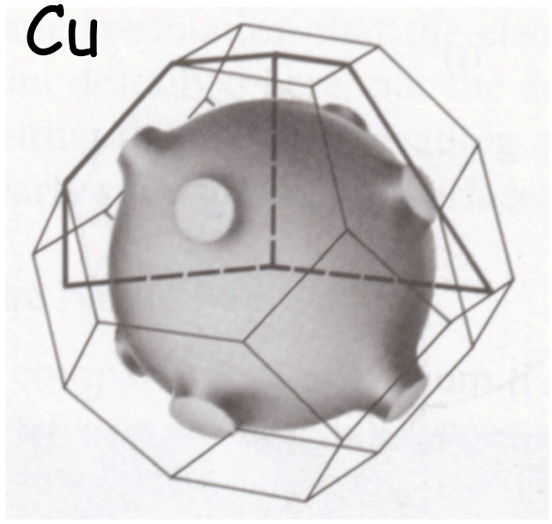


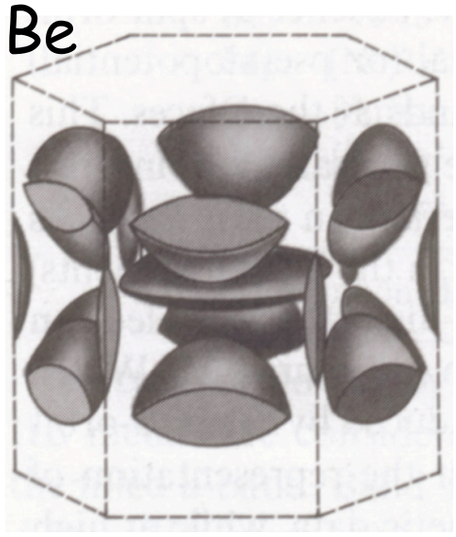


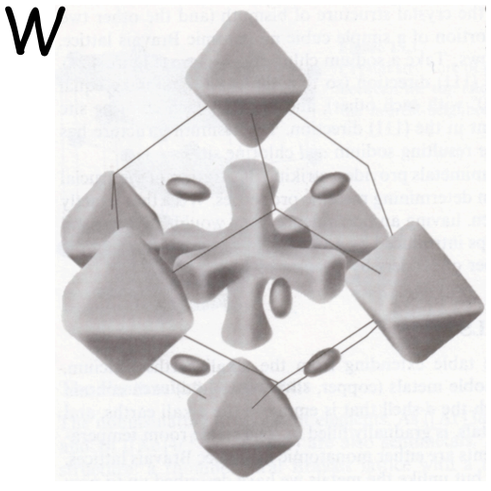


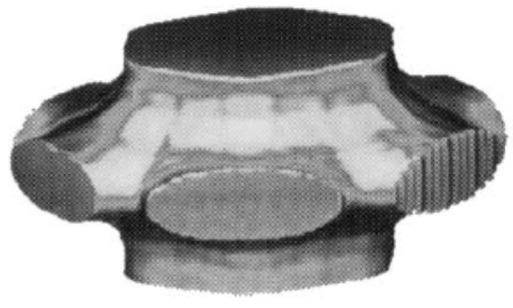
Band structure and Fermi surface - real world











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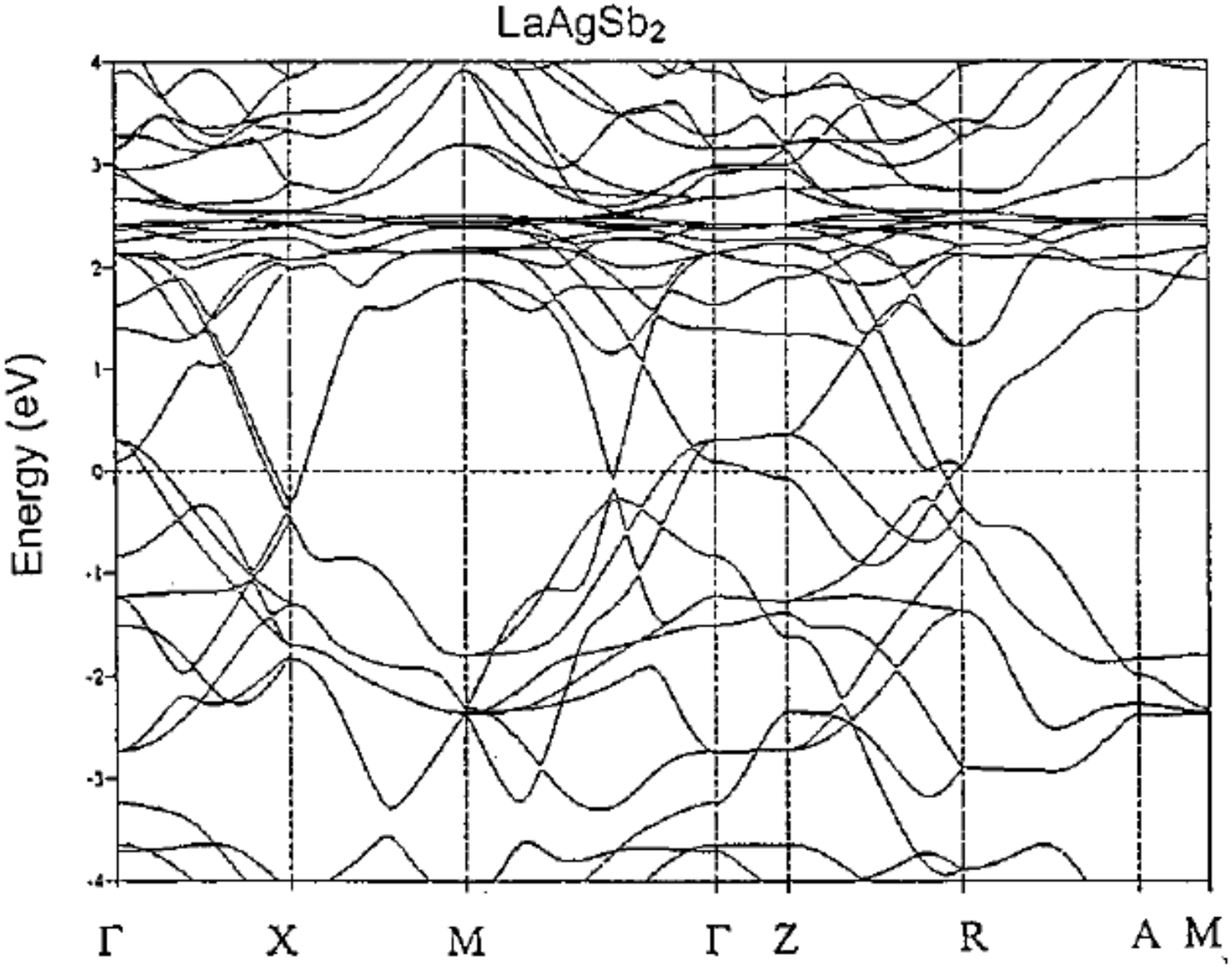
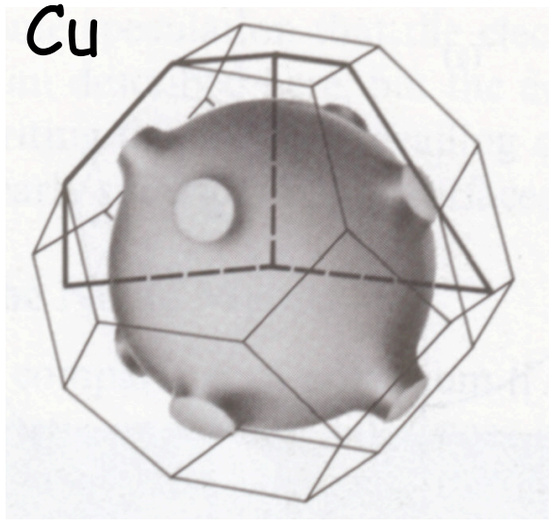
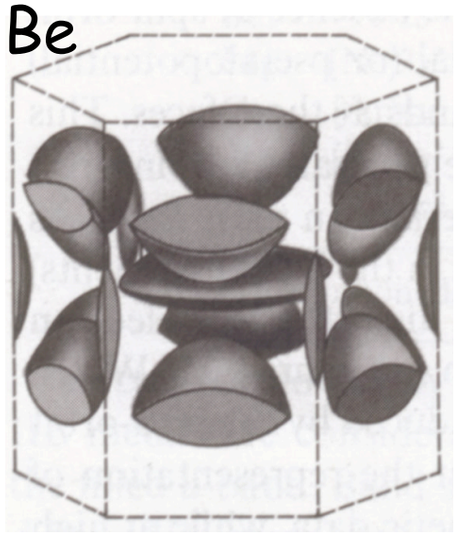
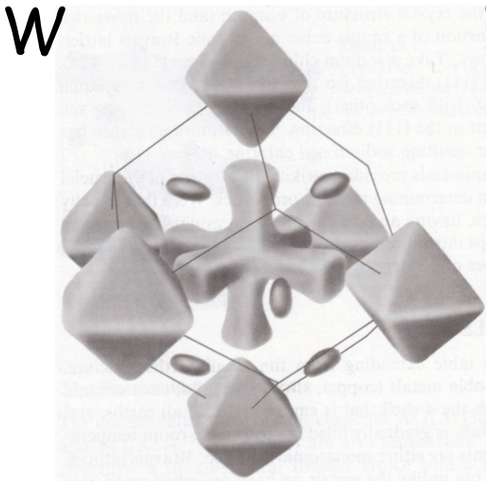
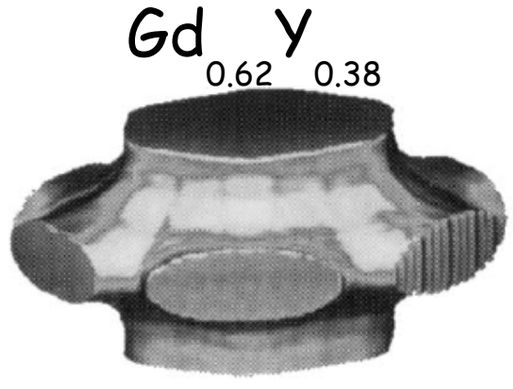
Band structure and Fermi surface - real world



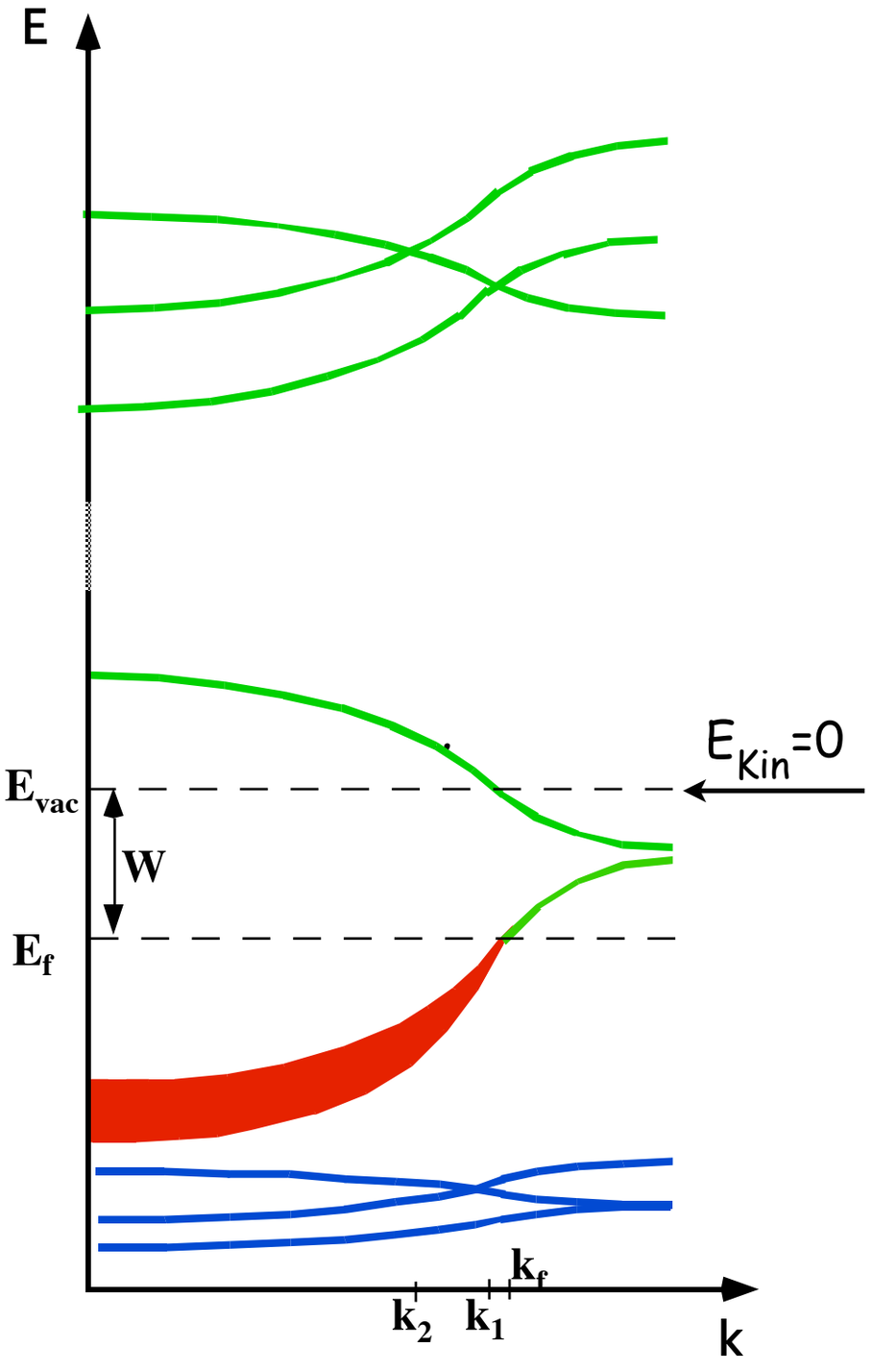






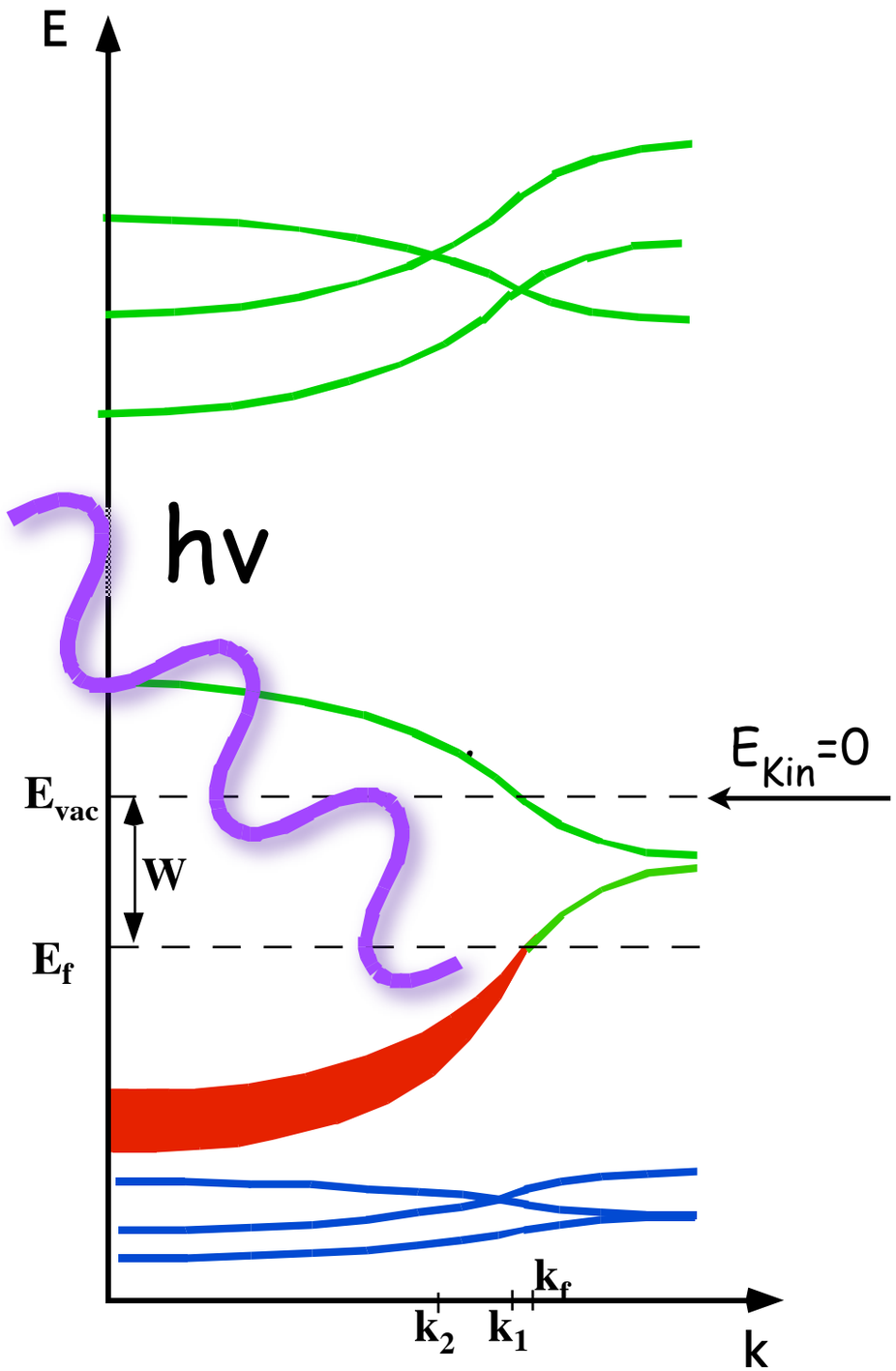


Electronic structure



ARPES spectra

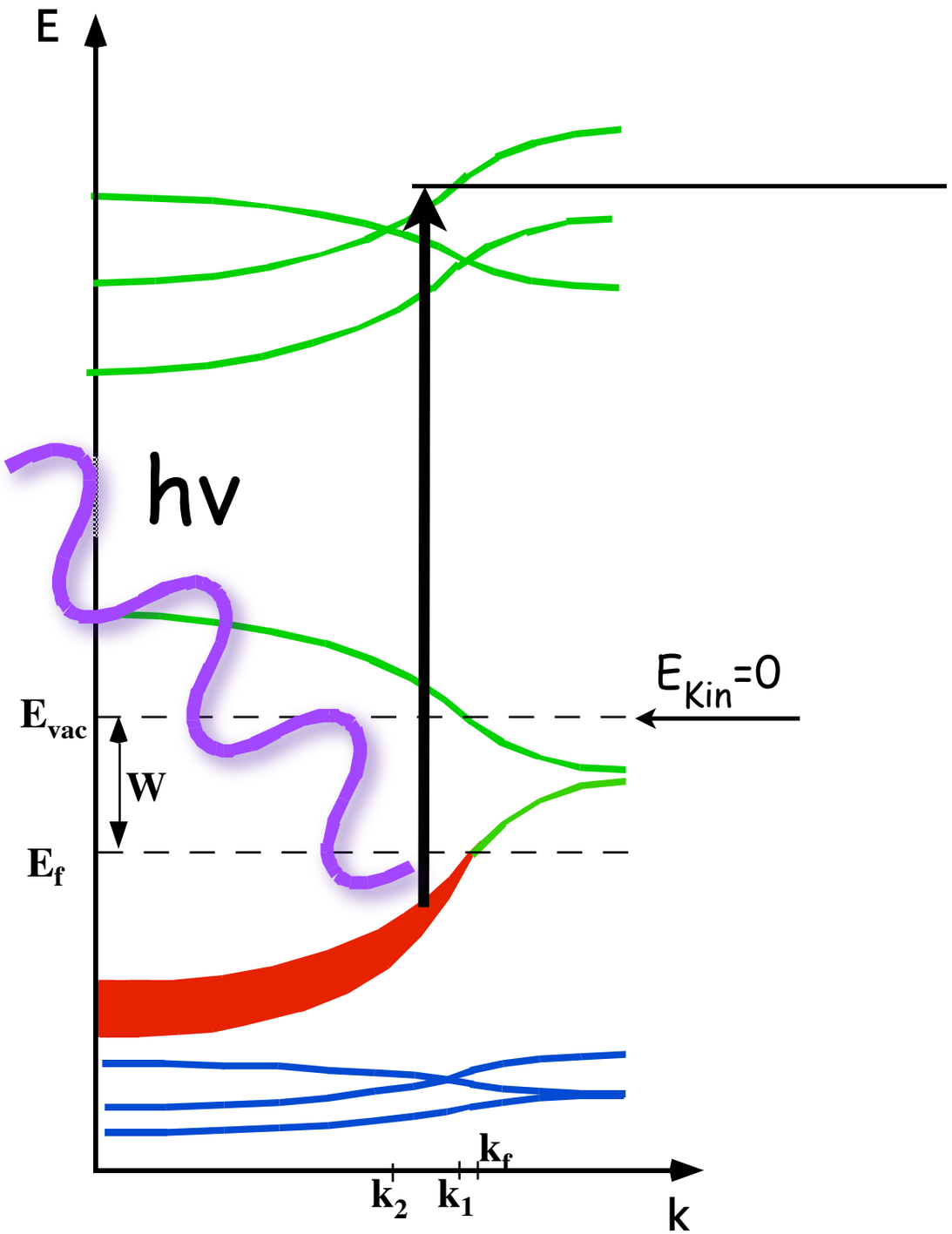
Electronic structure



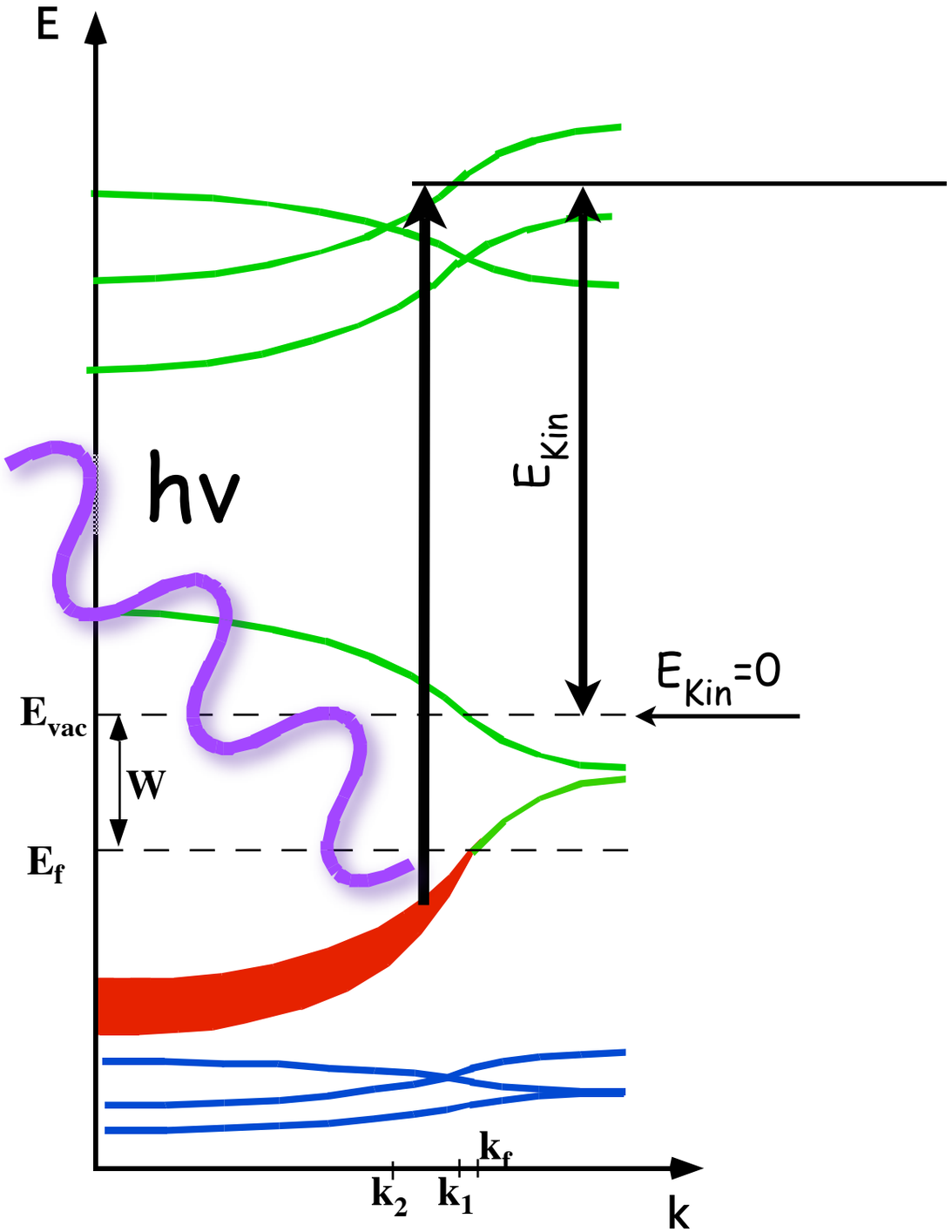
ARPES spectra

Electronic structure

ARPES spectra



Electronic structure



ARPES spectra

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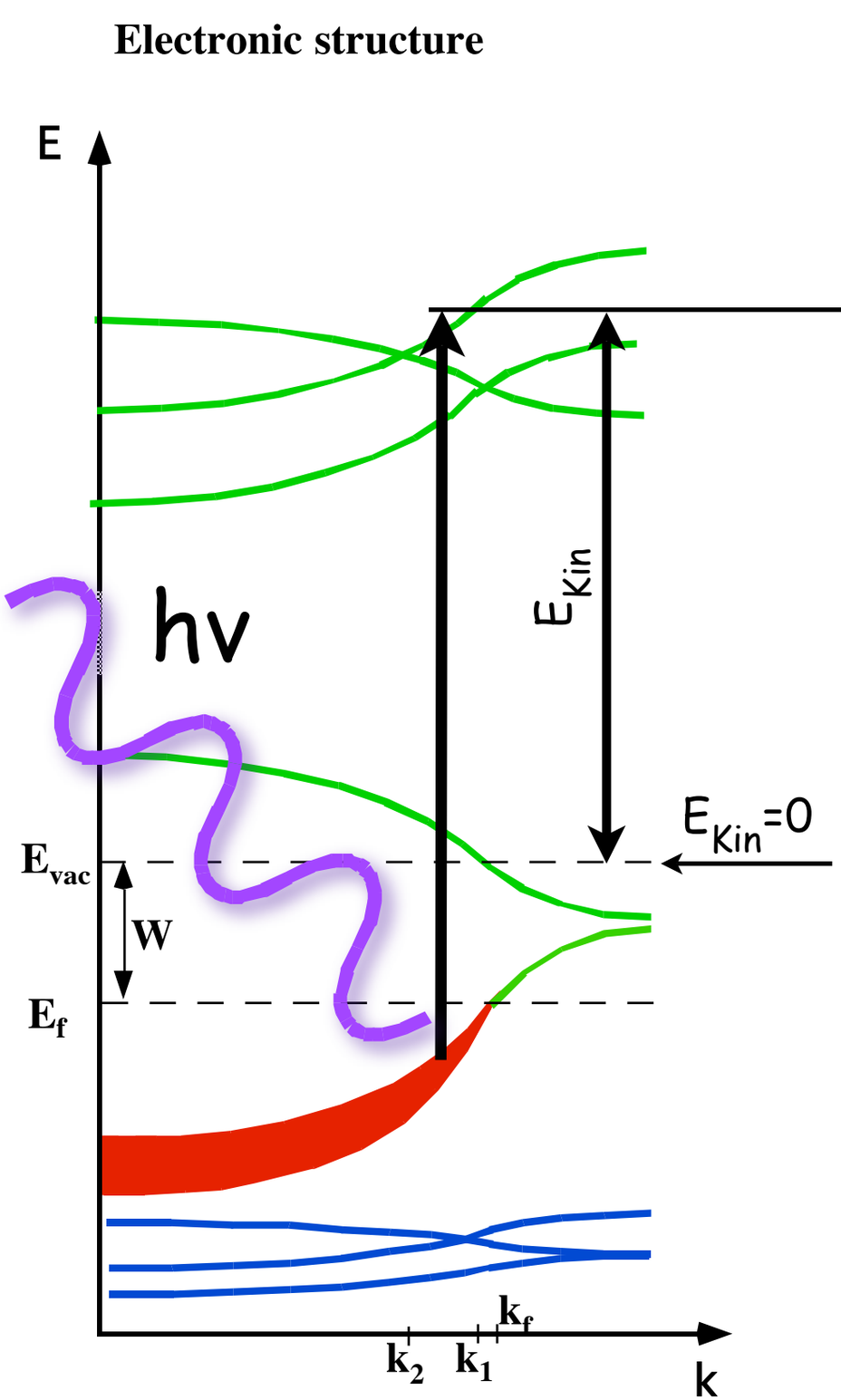

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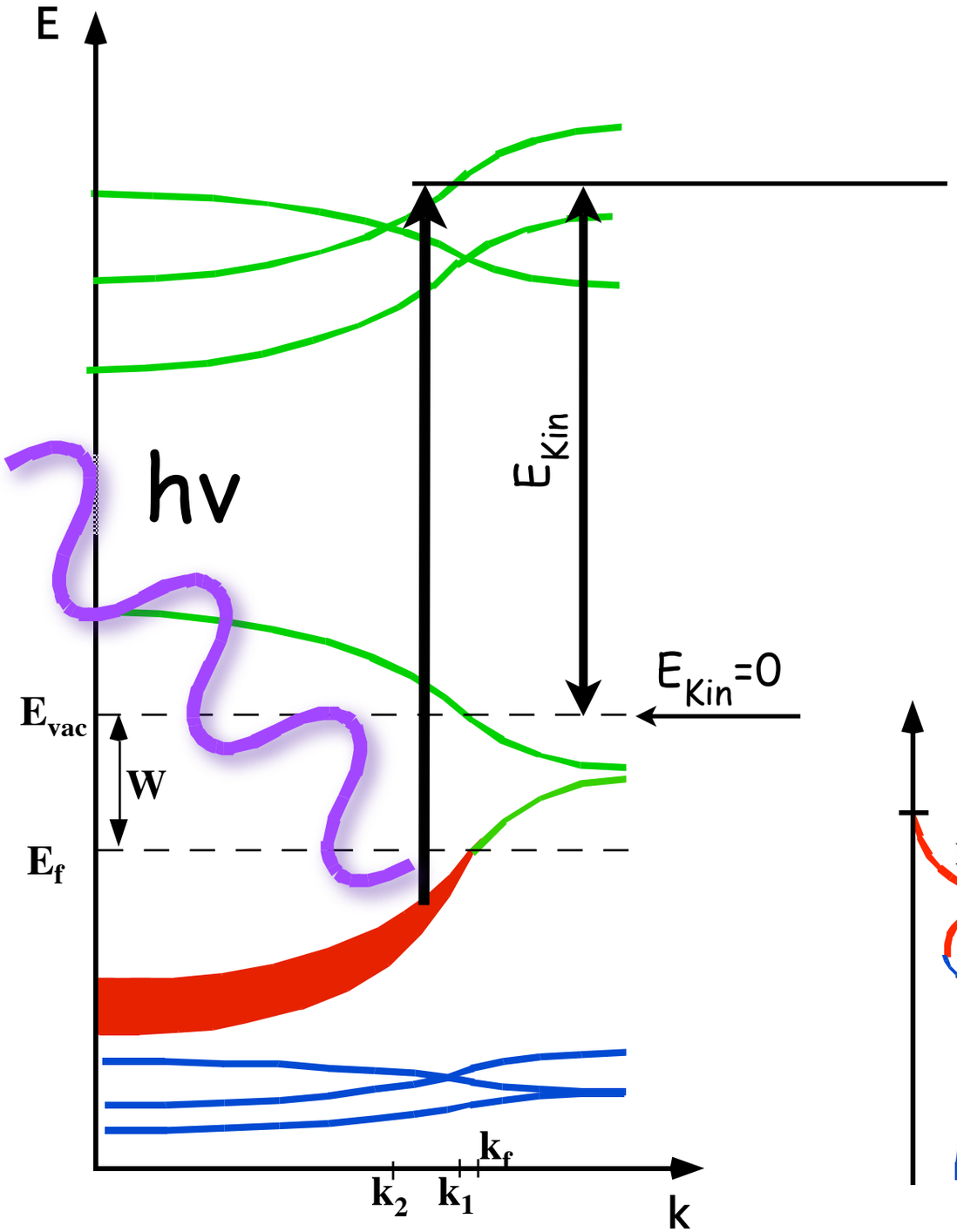
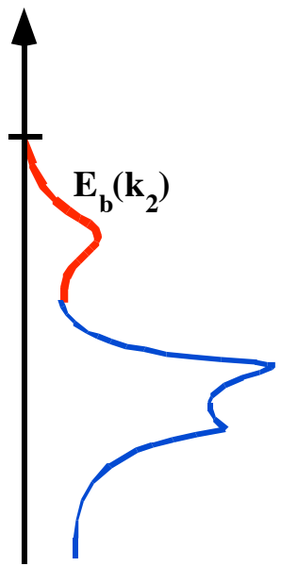
Electronic structure

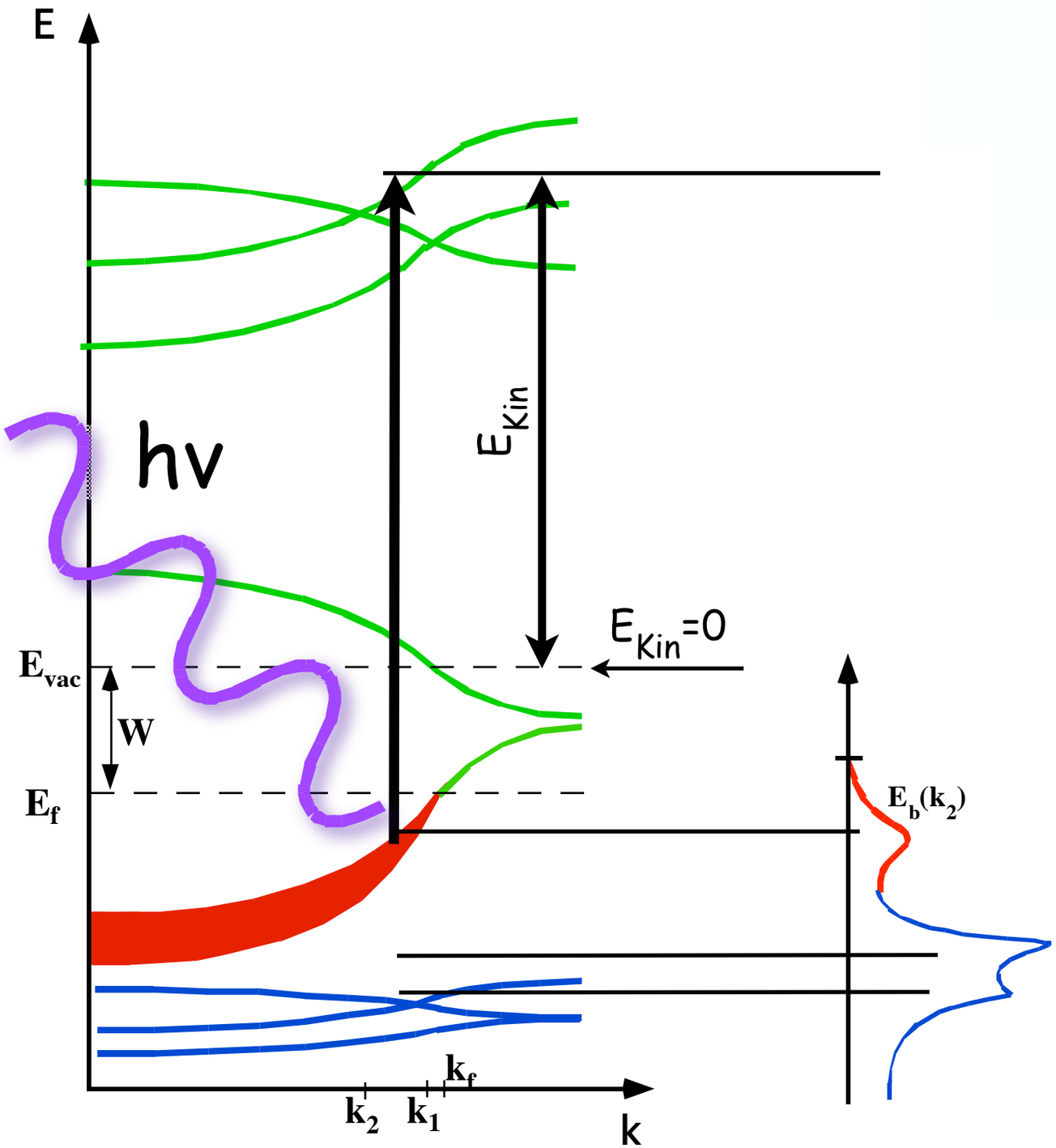


ARPES spectra

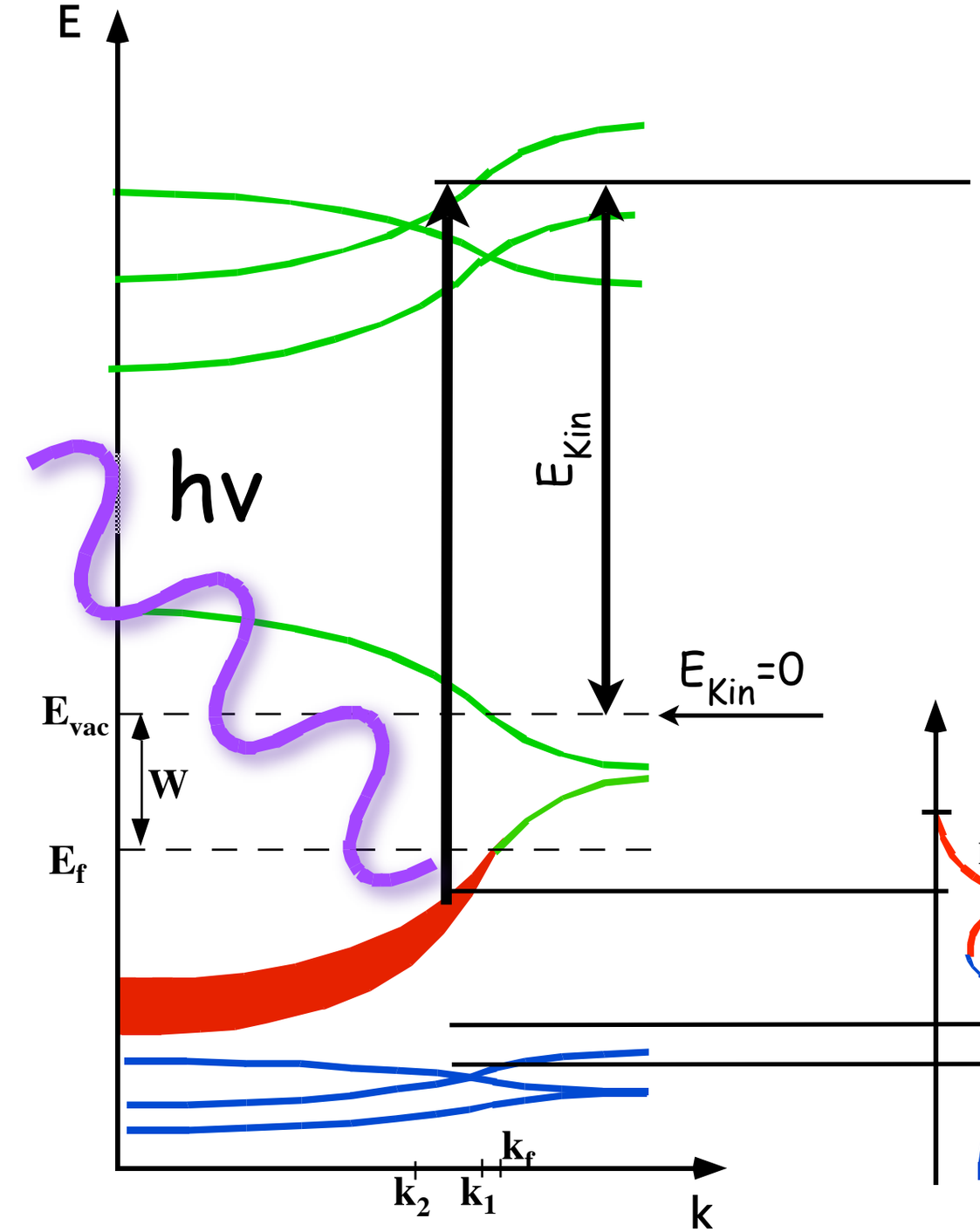


Electronic structure

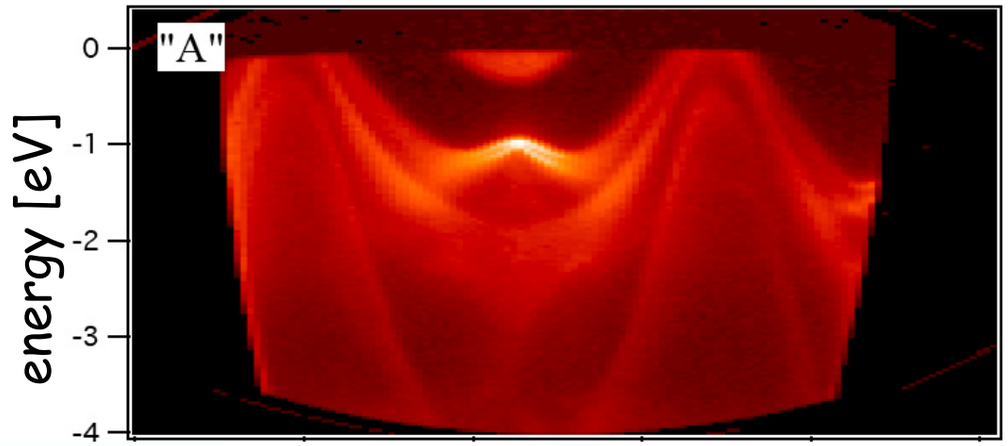
ARPES spectra



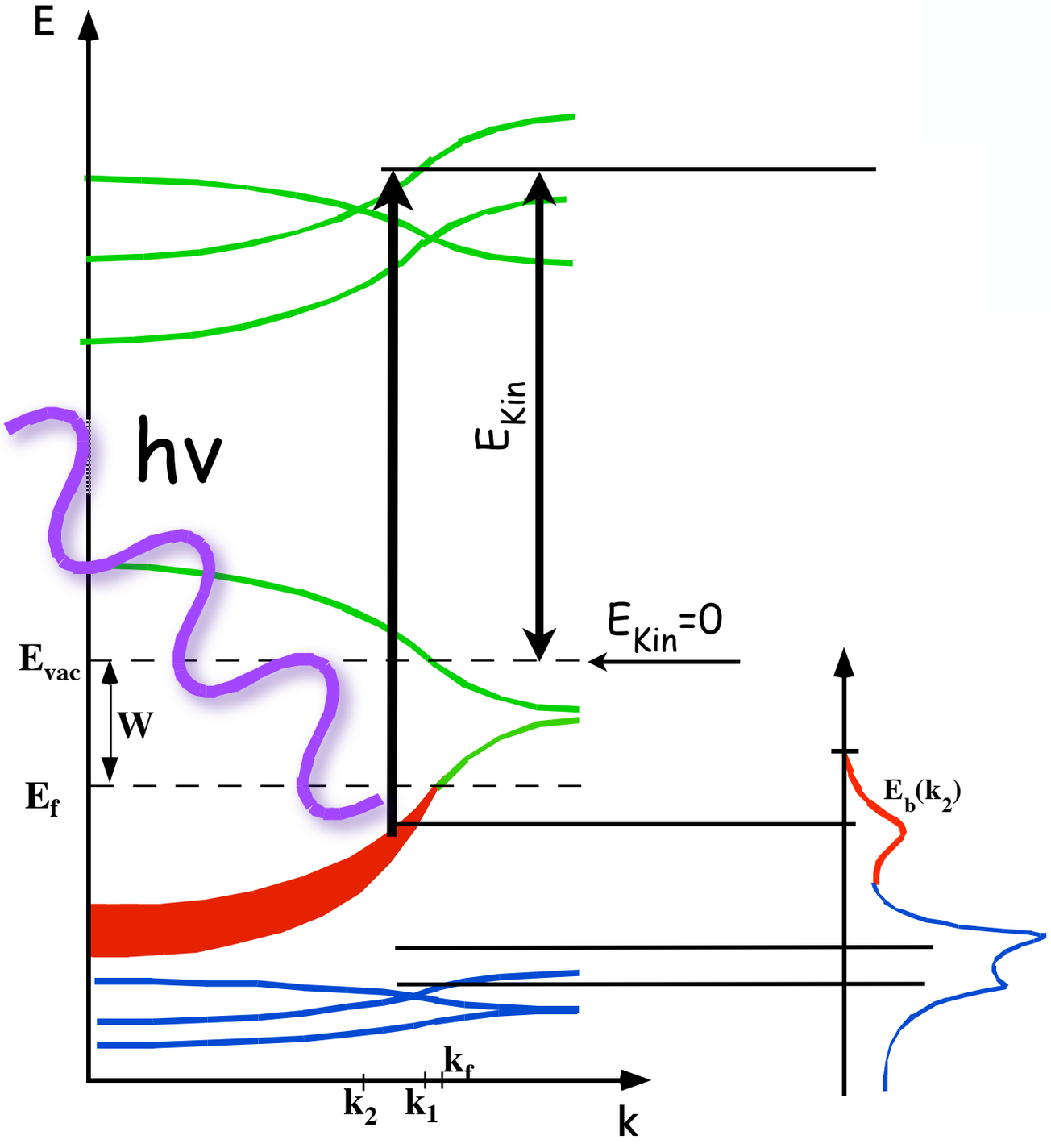
Electronic structure



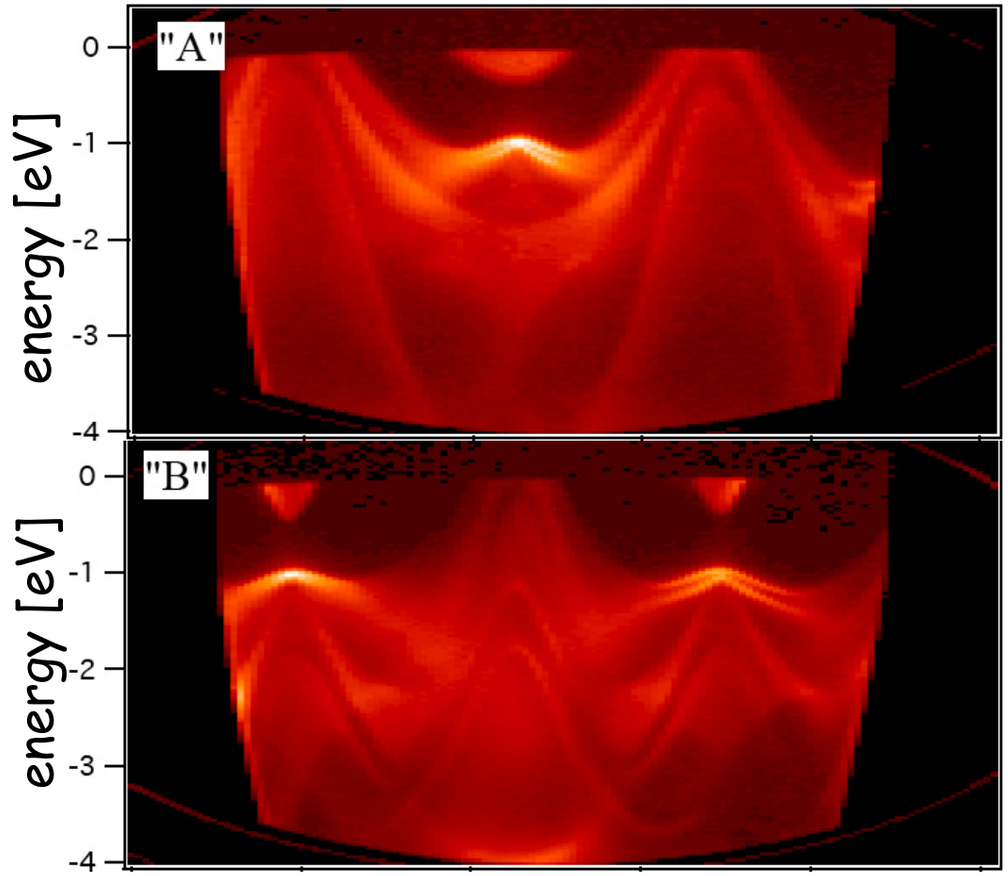
ARPES spectra



Electronic structure



ARPES spectra



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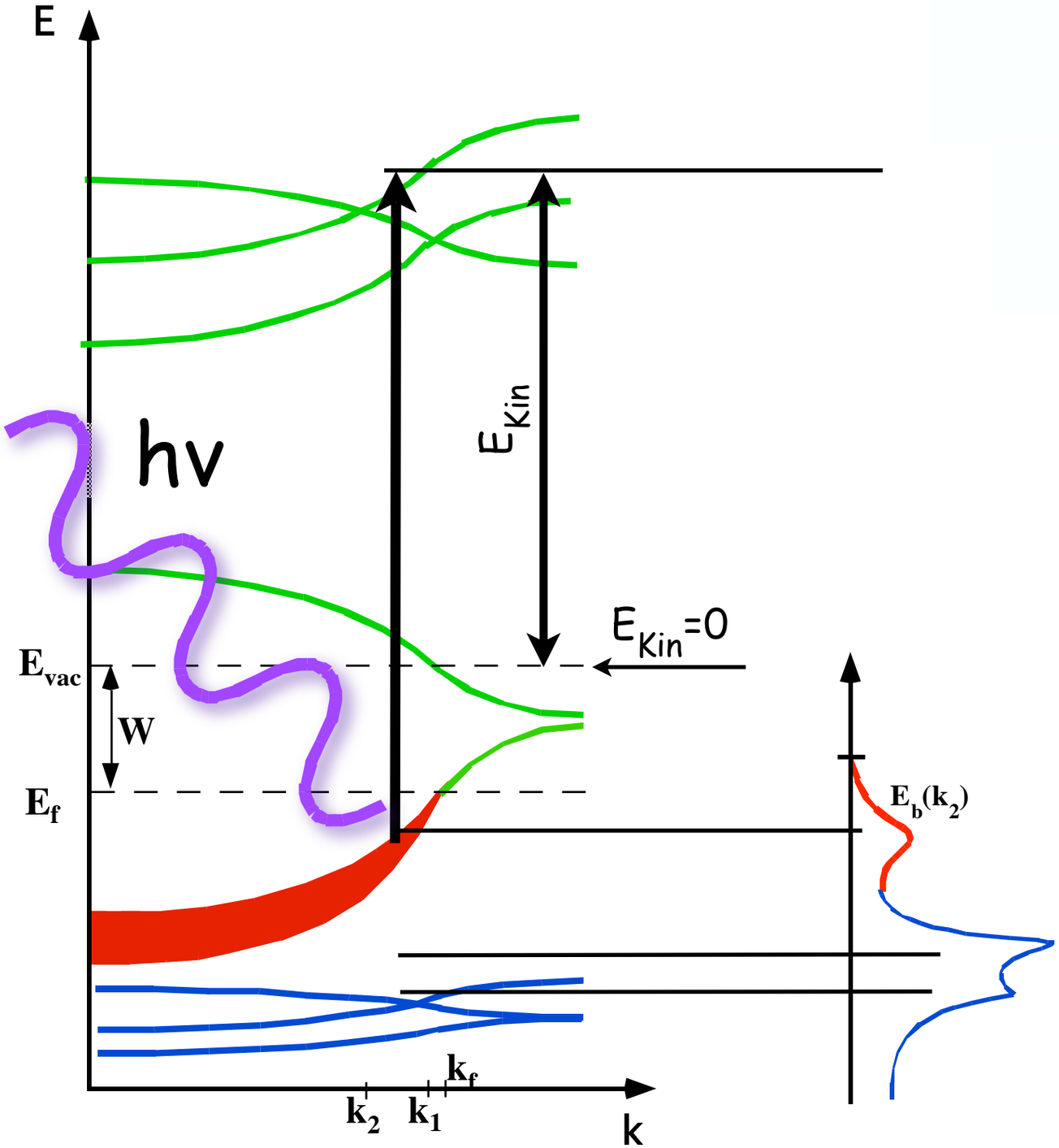
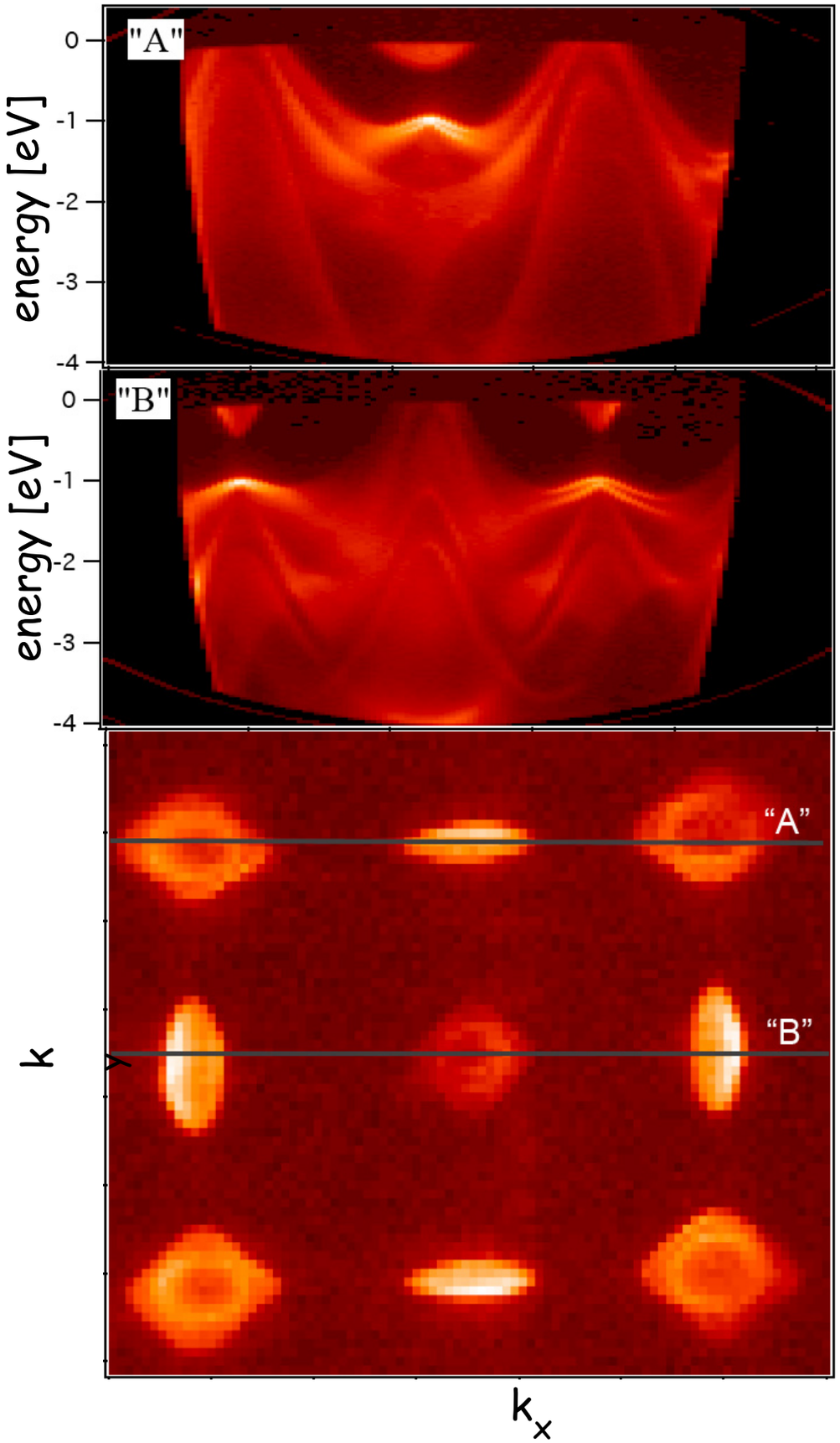


ARPES spectra



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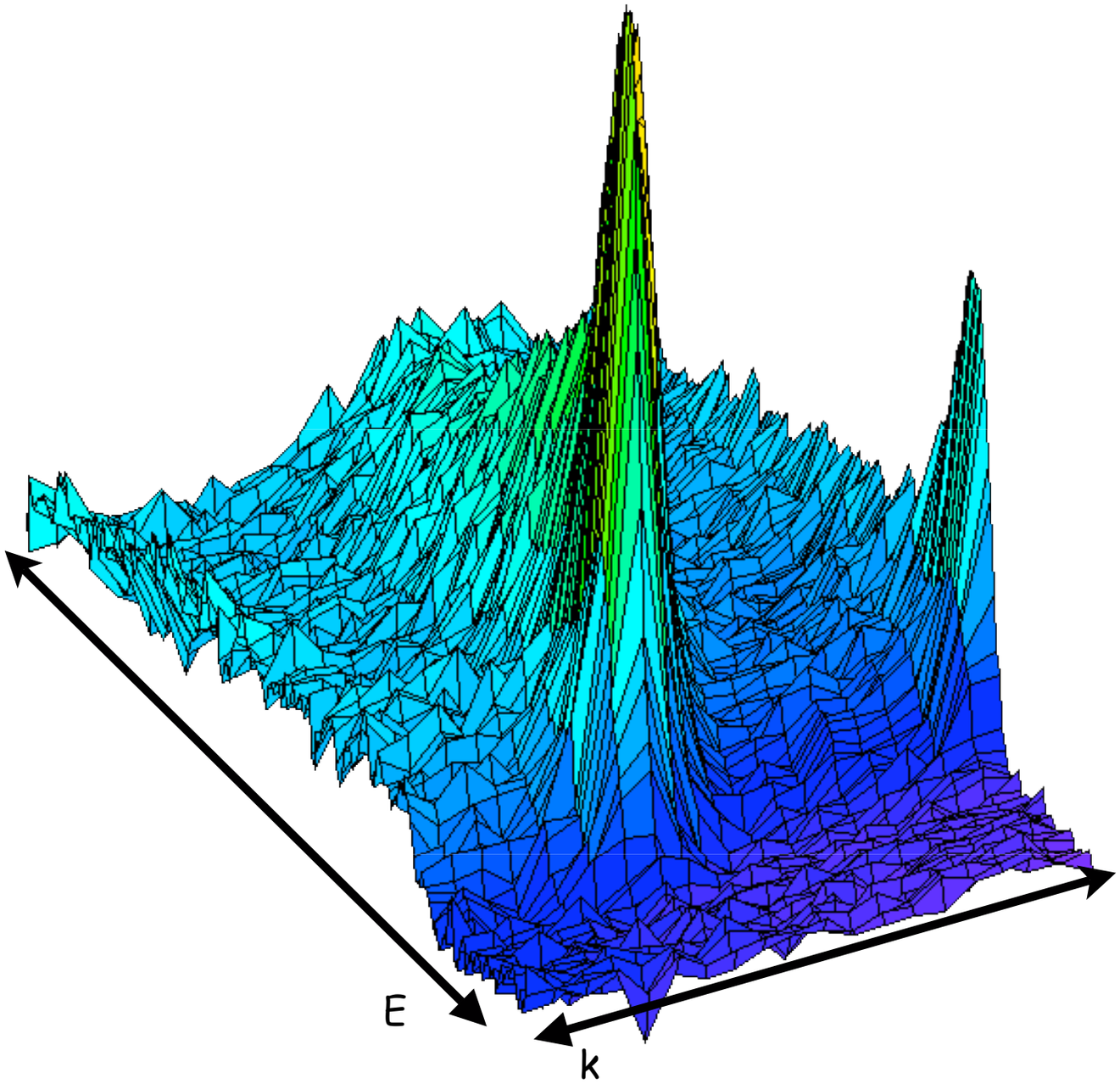

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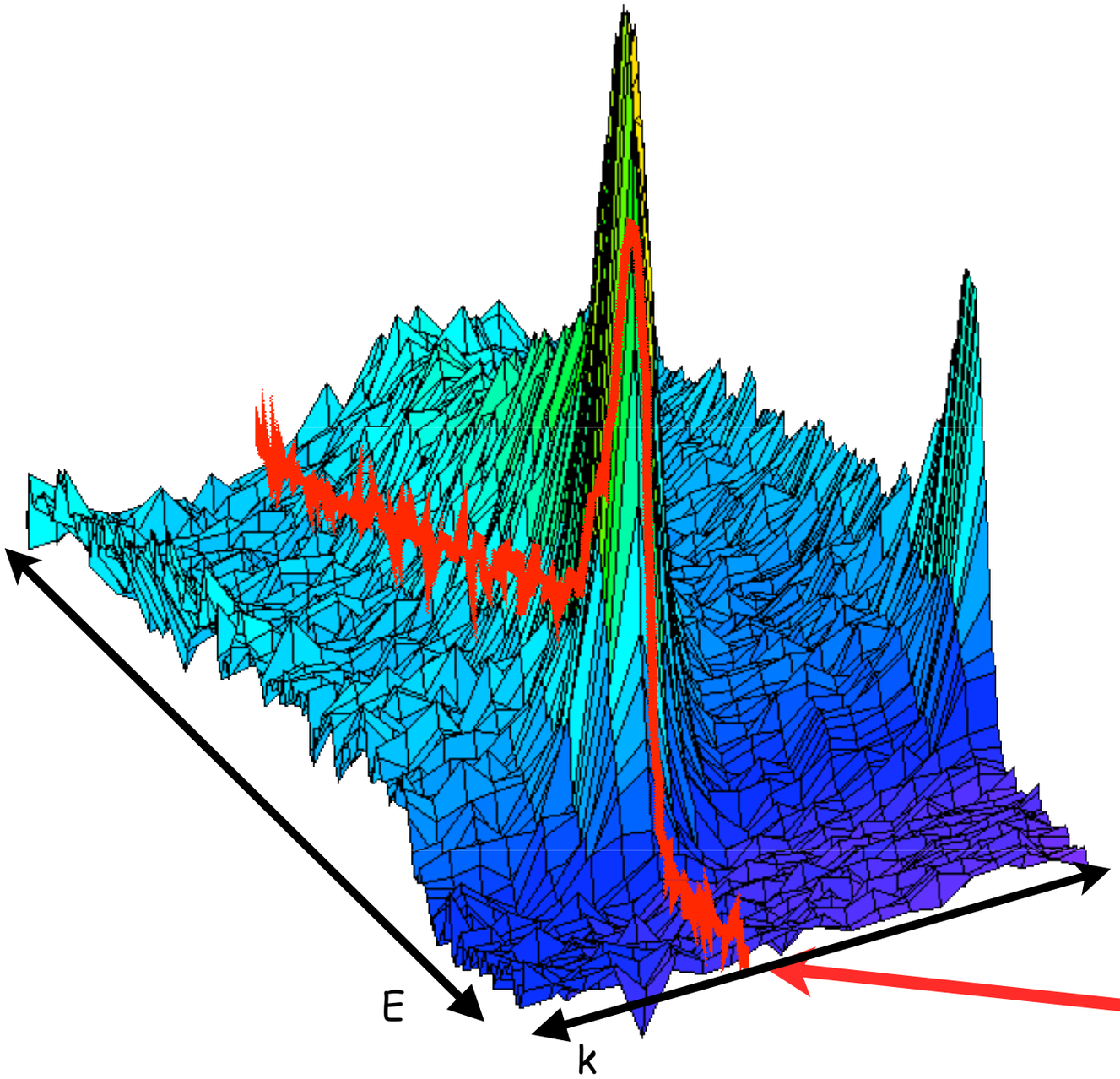

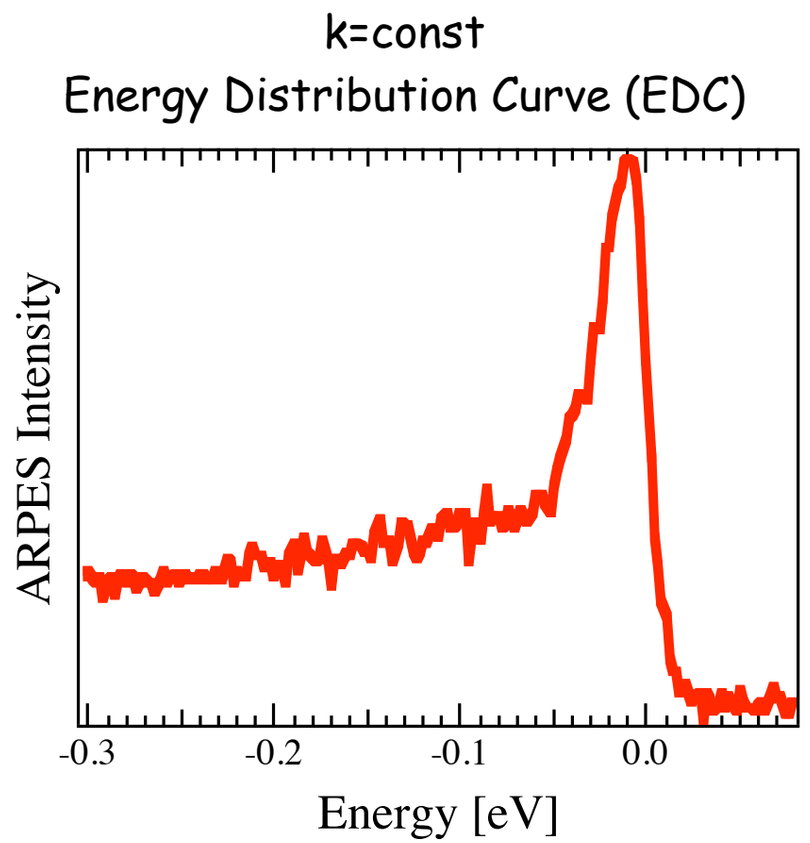

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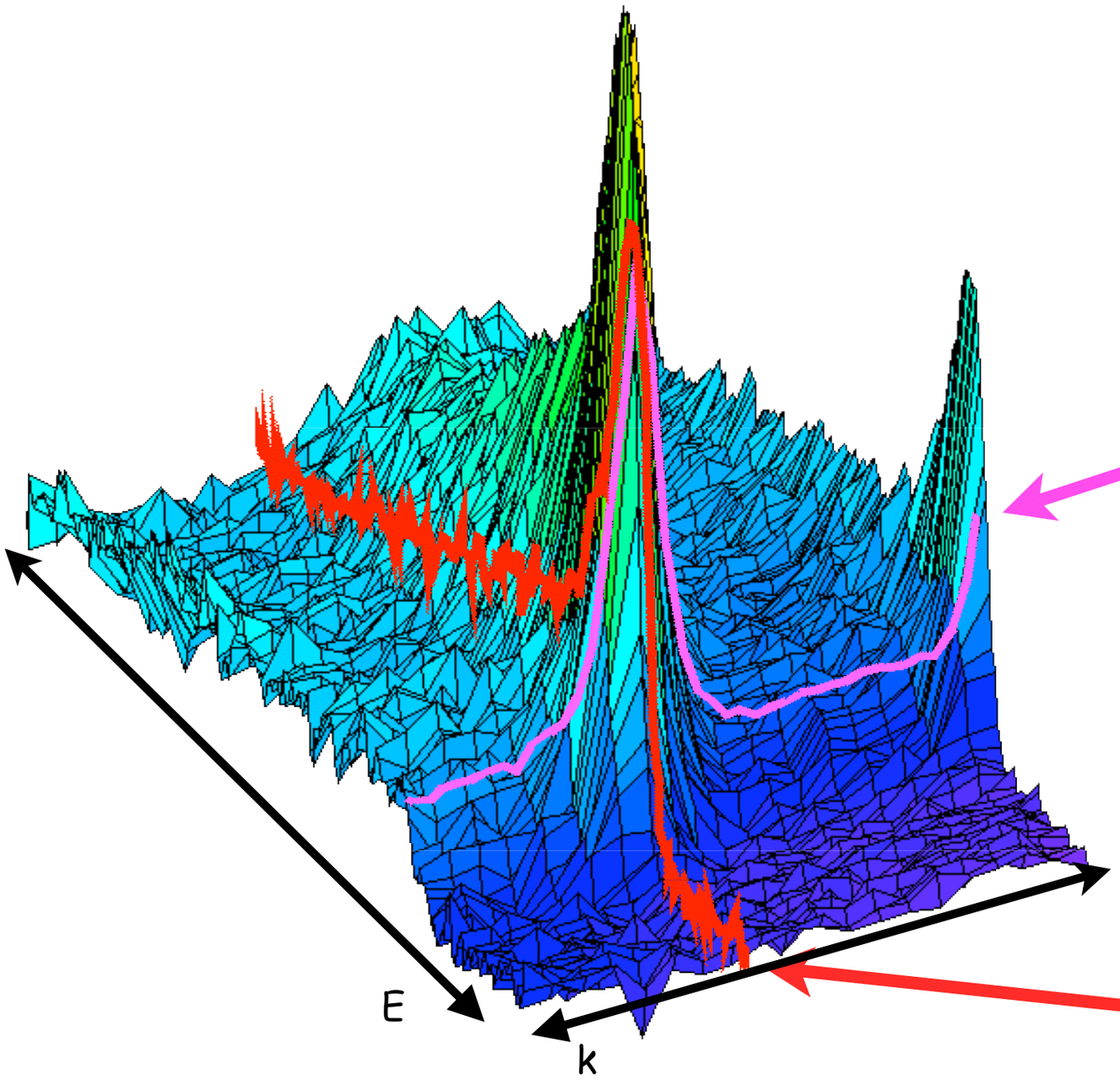
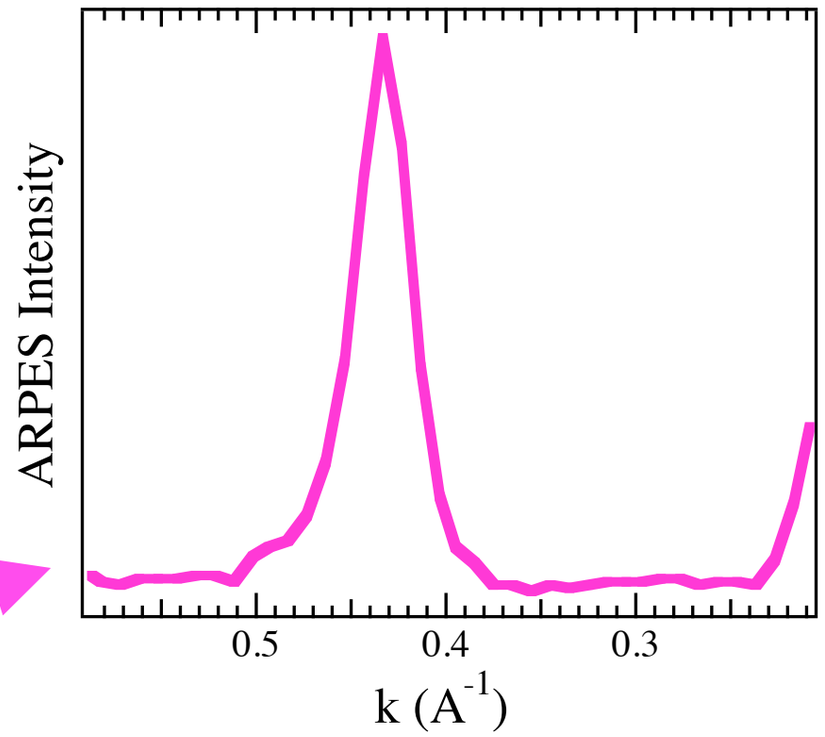
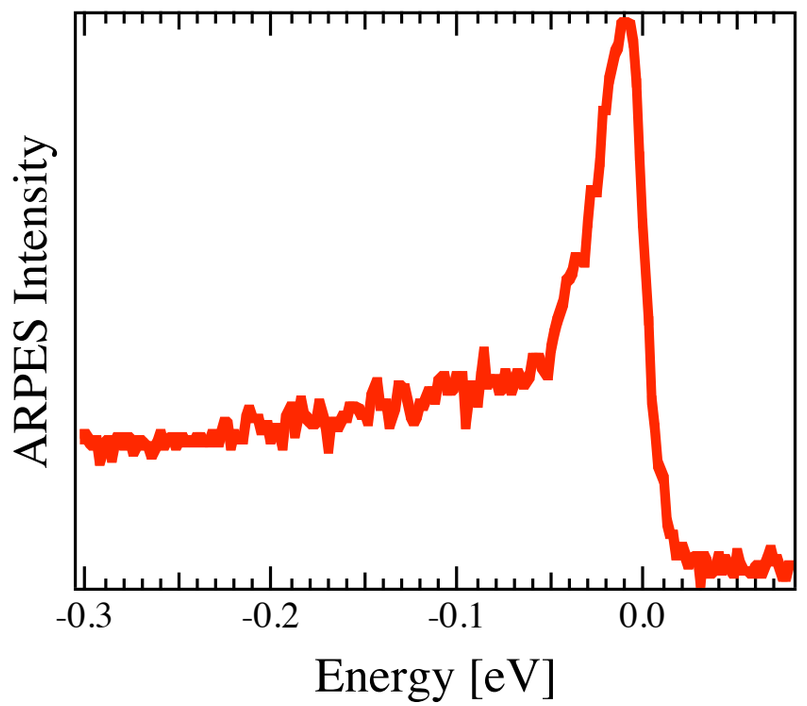


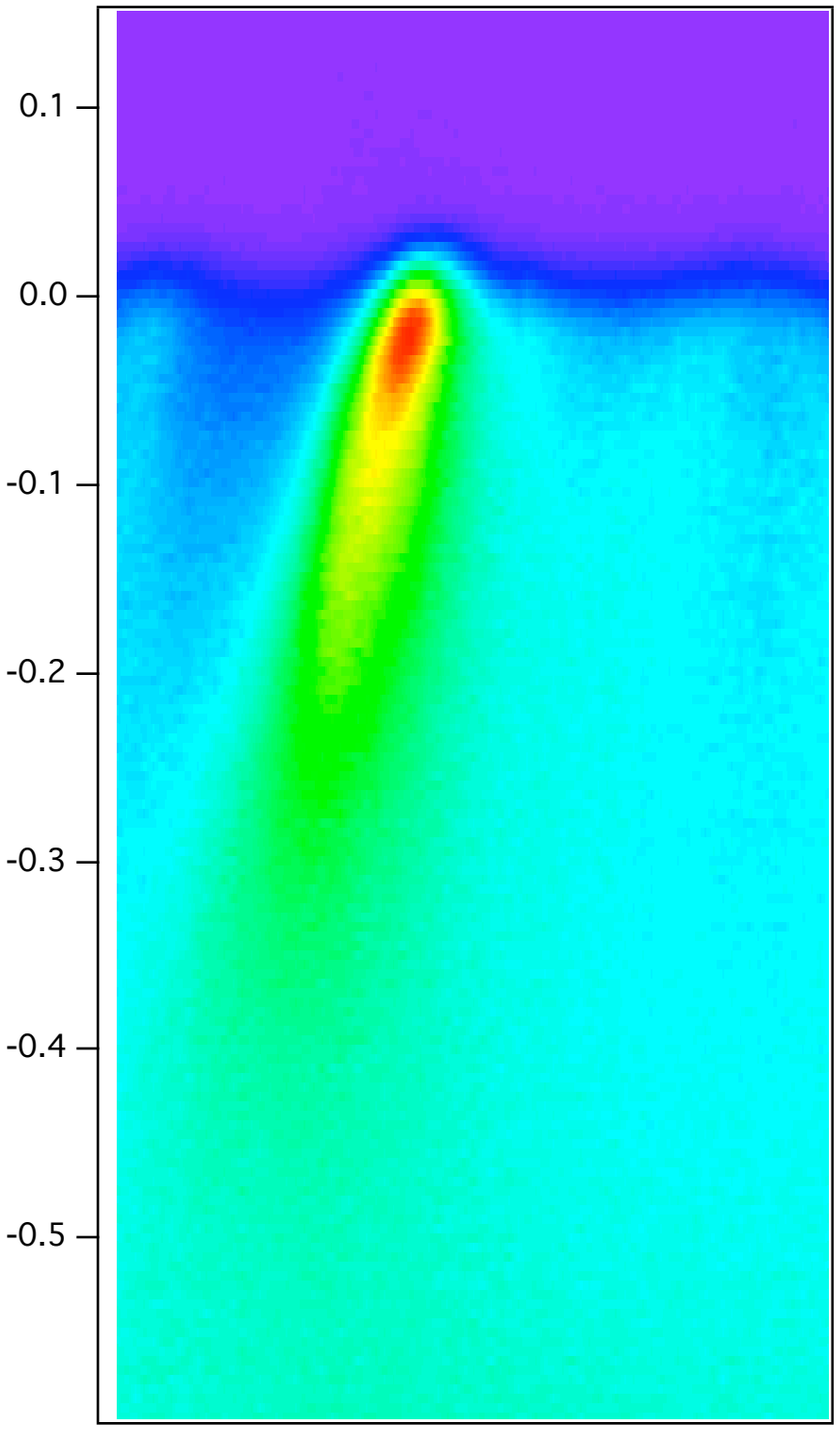
E=const
Momentum Distribution Curve (MDC)



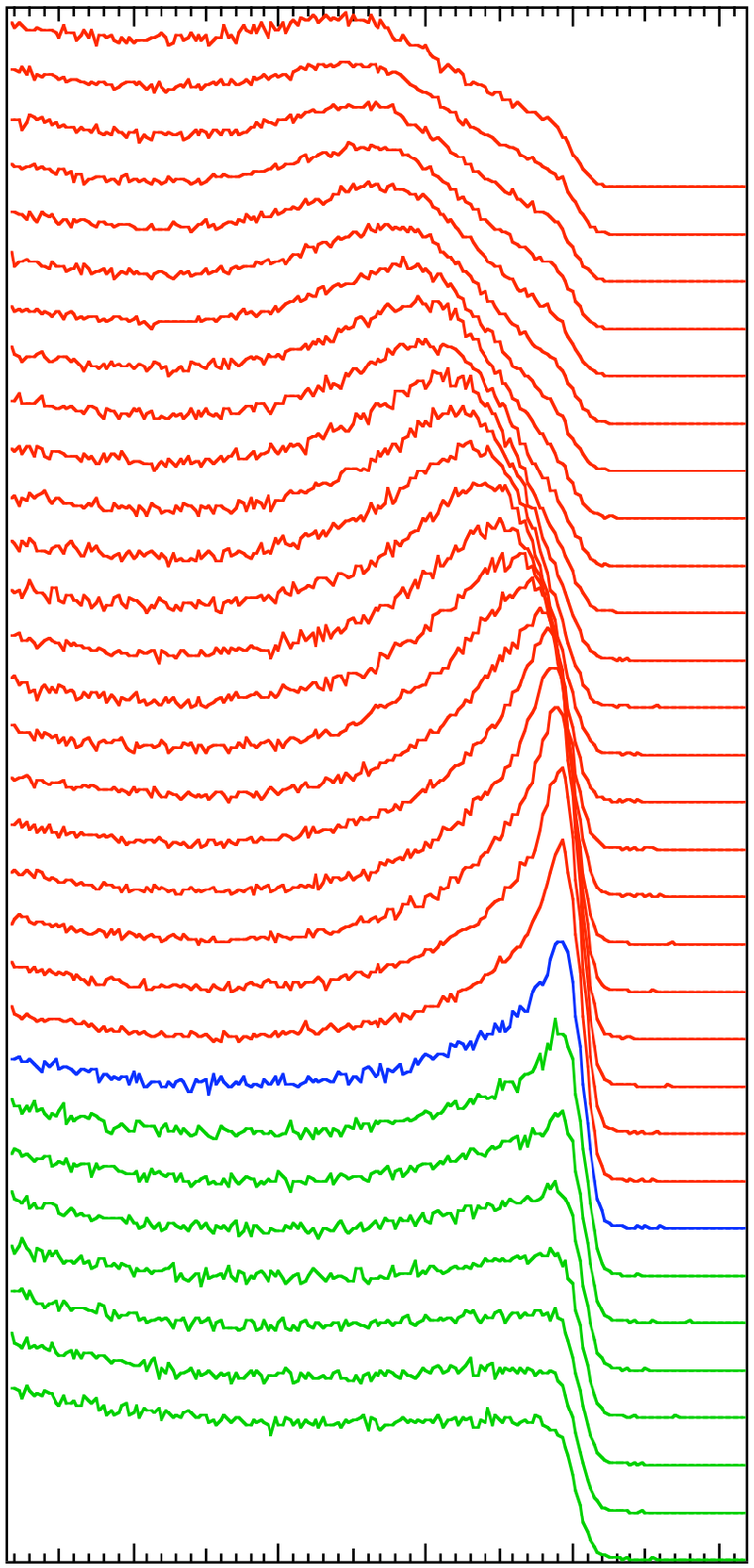
k=const
Energy Distribution Curve (EDC)



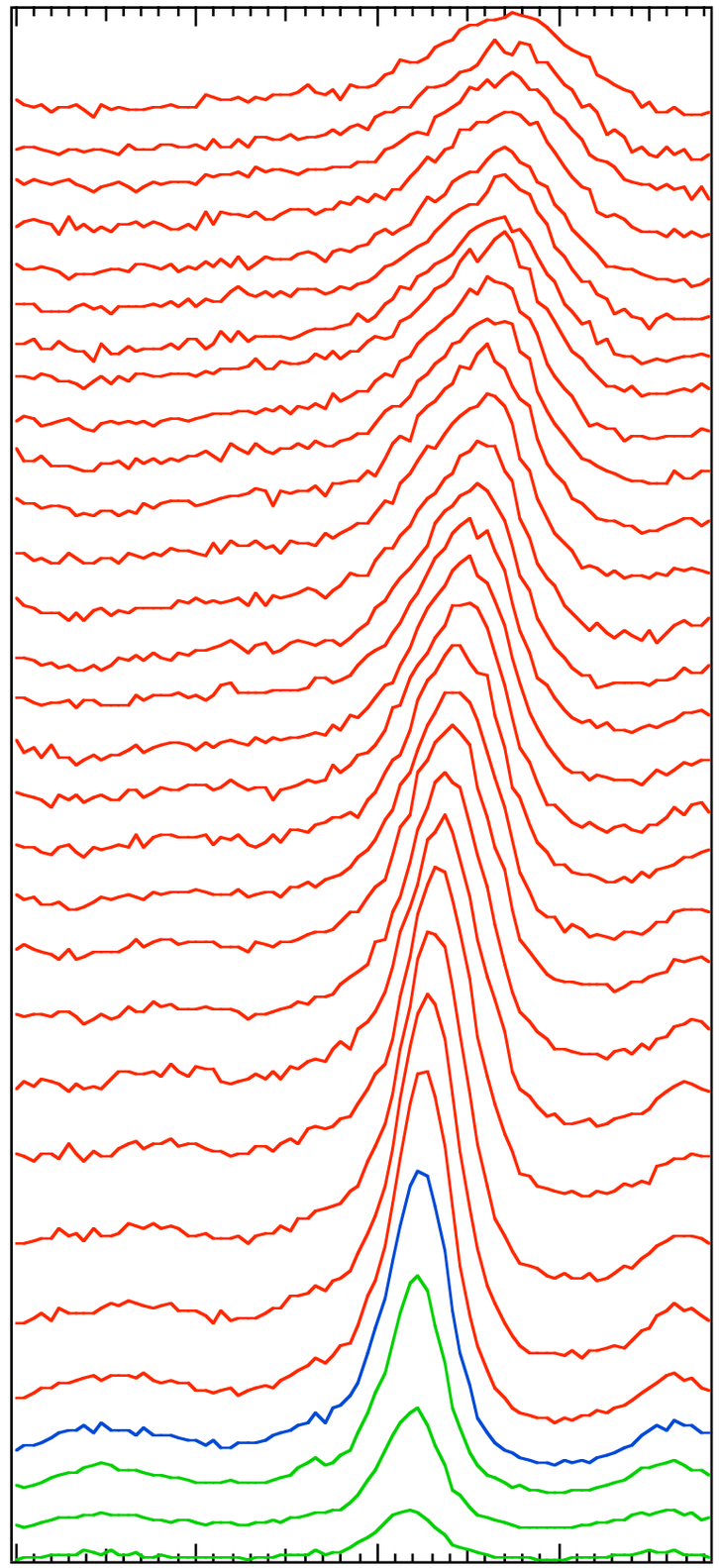
Intensity plot



EDC



MDC



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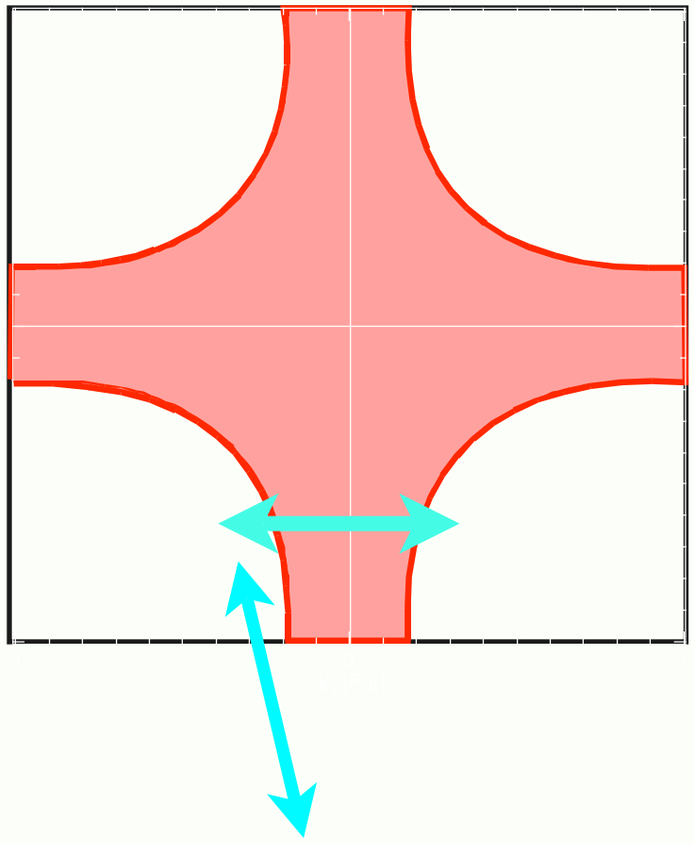
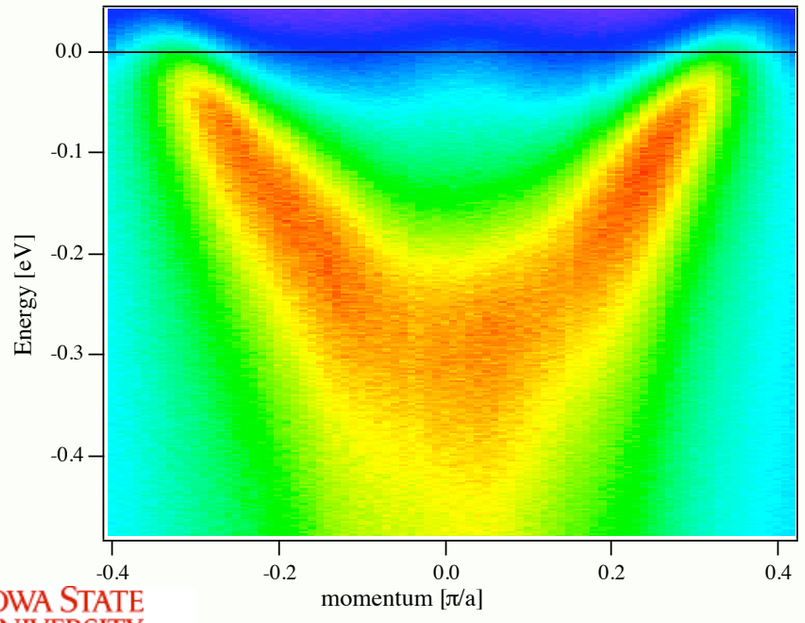
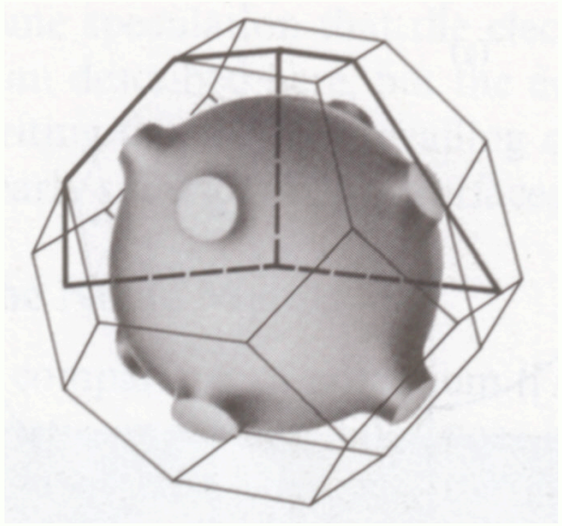
2D

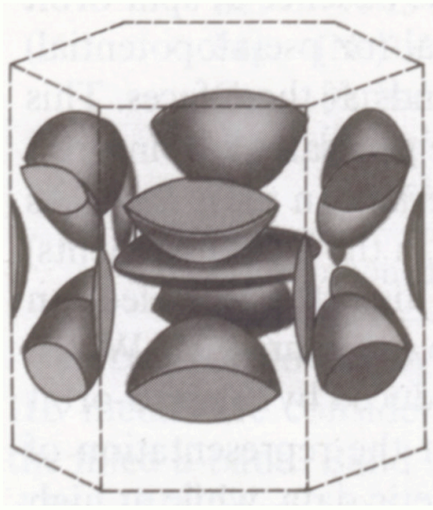




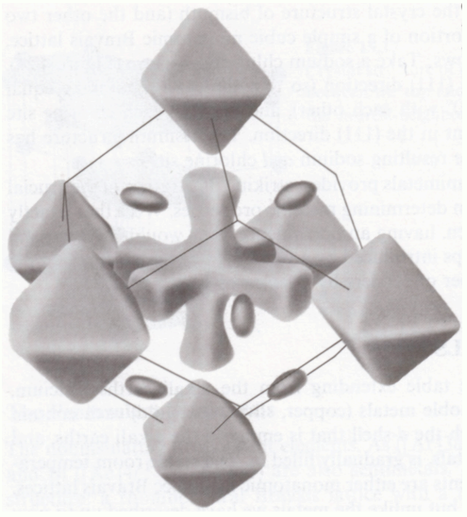
3D



Cu



Be



W

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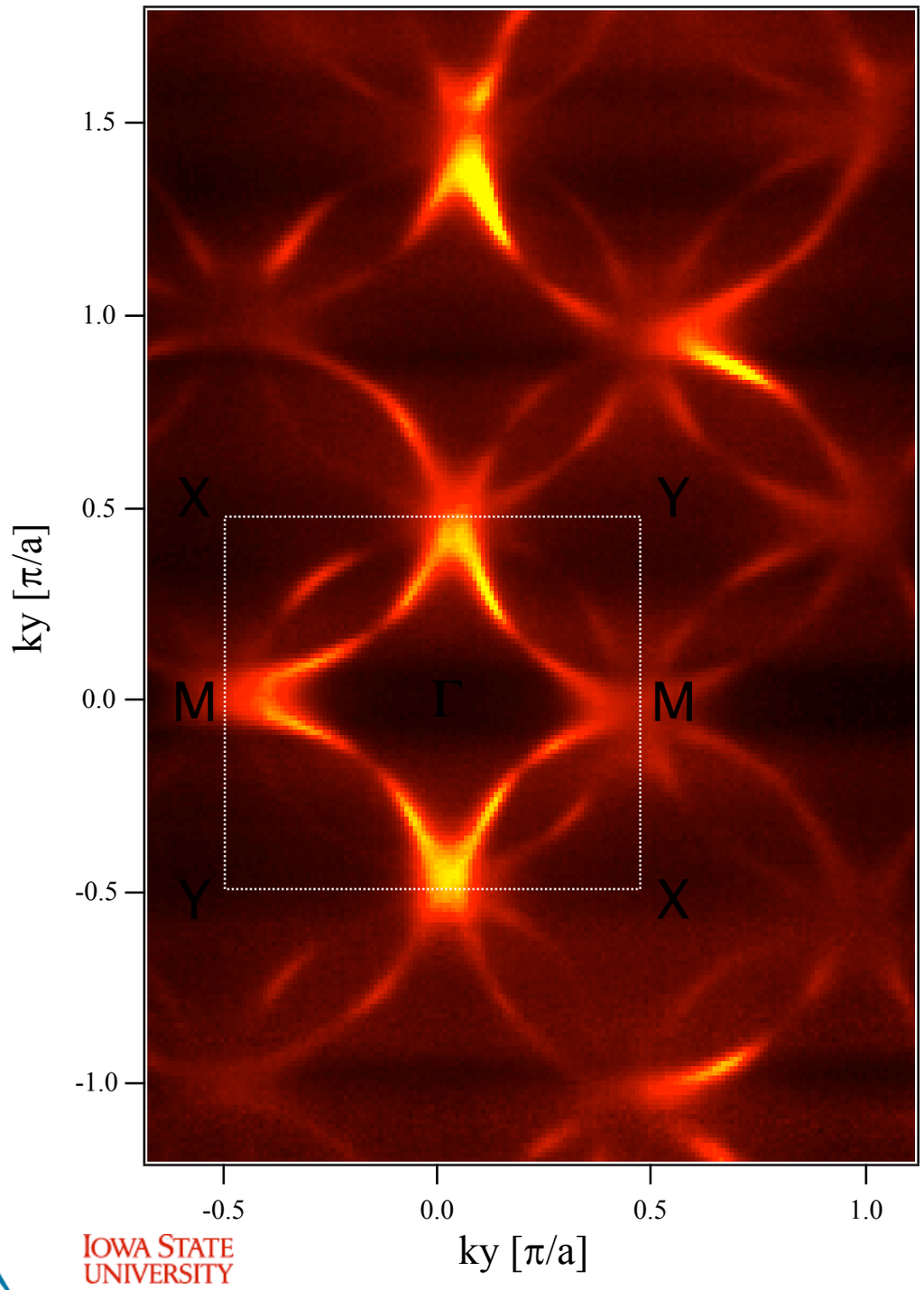
Fermi surface of high temperature superconductor

$Bi_2Sr_2Cu_1O_{6+x}$ (Tc=35K)



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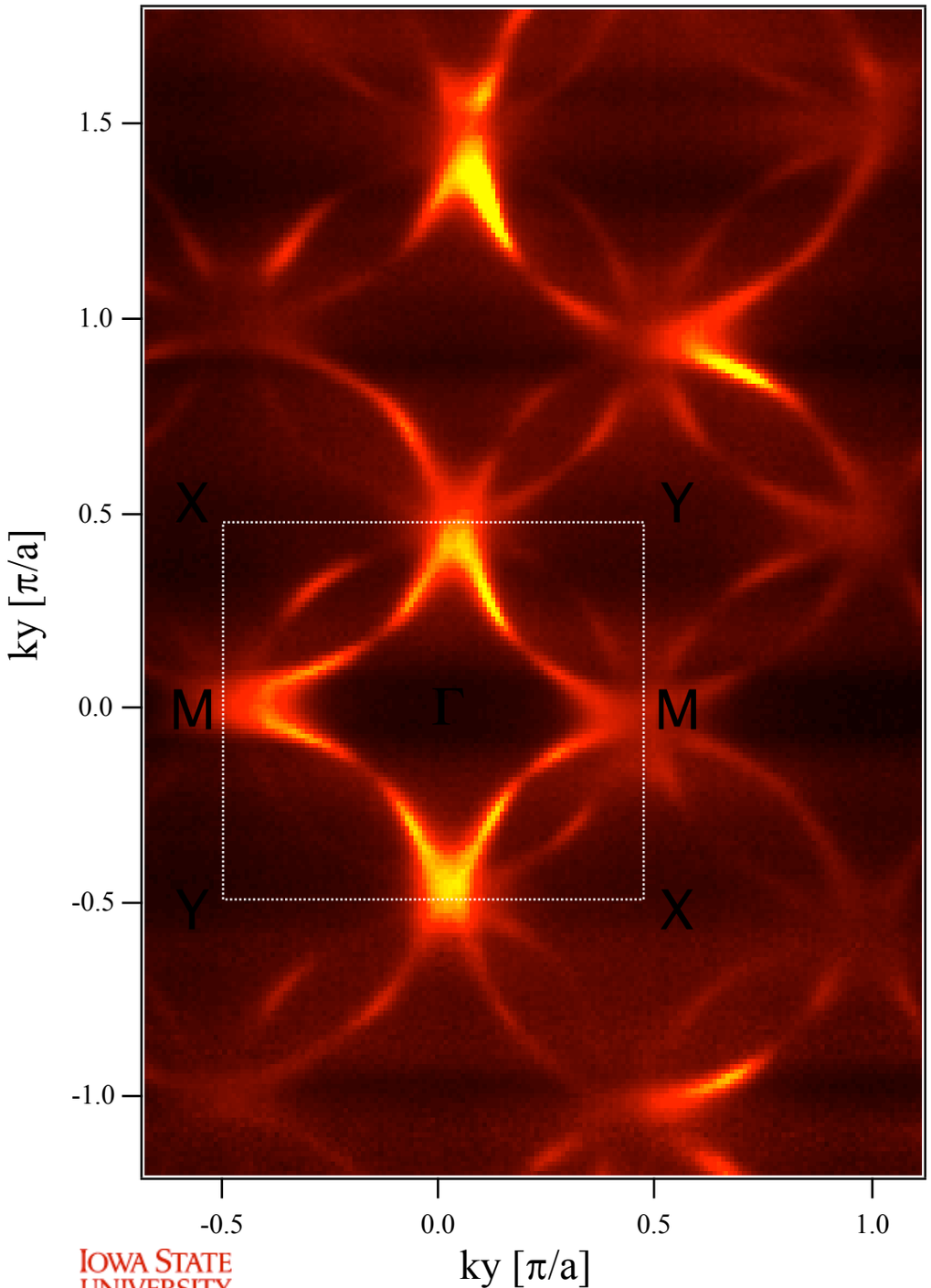
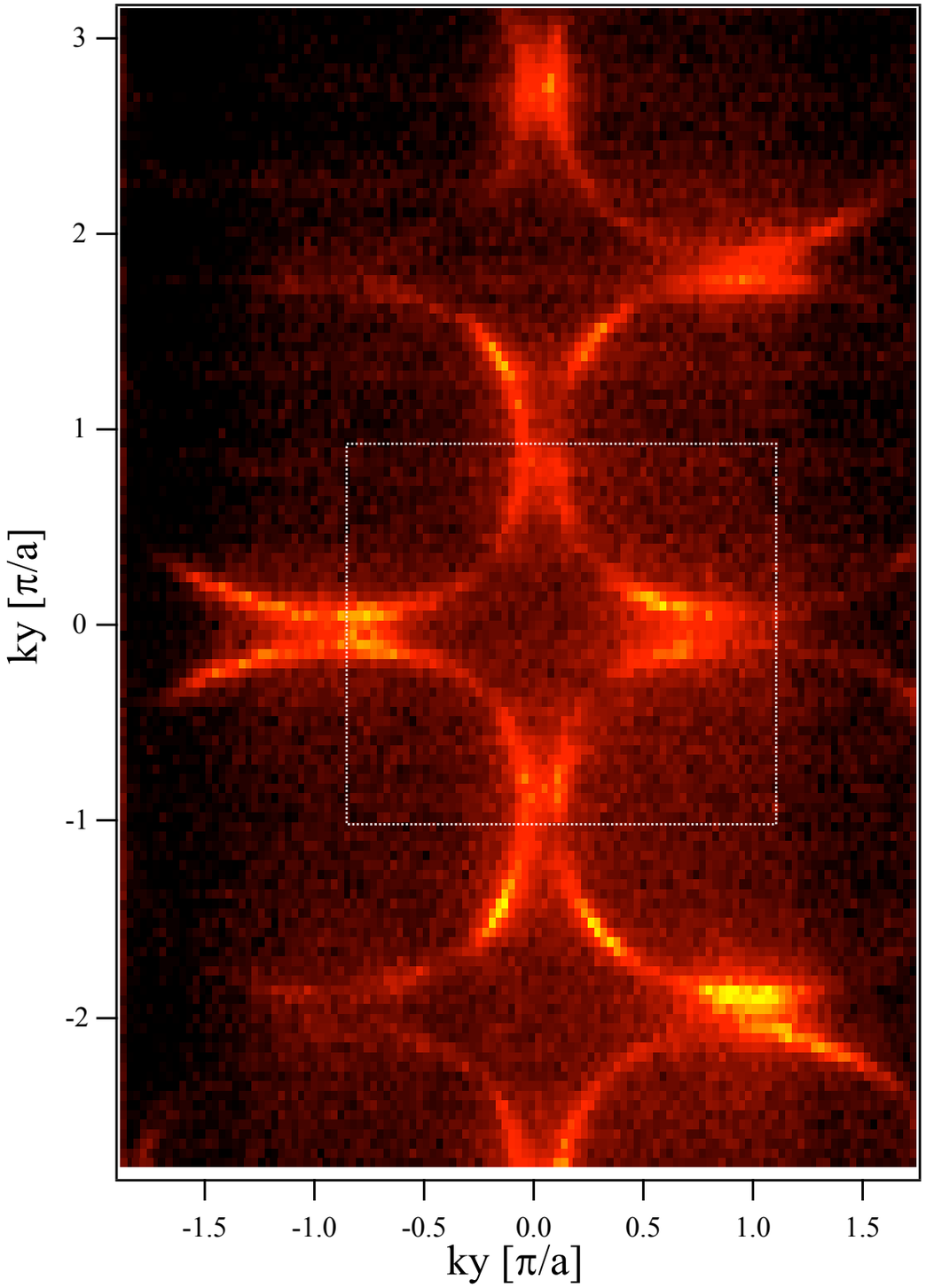
Fermi surface of high temperature superconductor

$Bi_2Sr_2Cu_1O_{6+x}$ (Tc=35K)



$Tl_2Ba_2Cu_1O_{6+x}$(Tc=90K)



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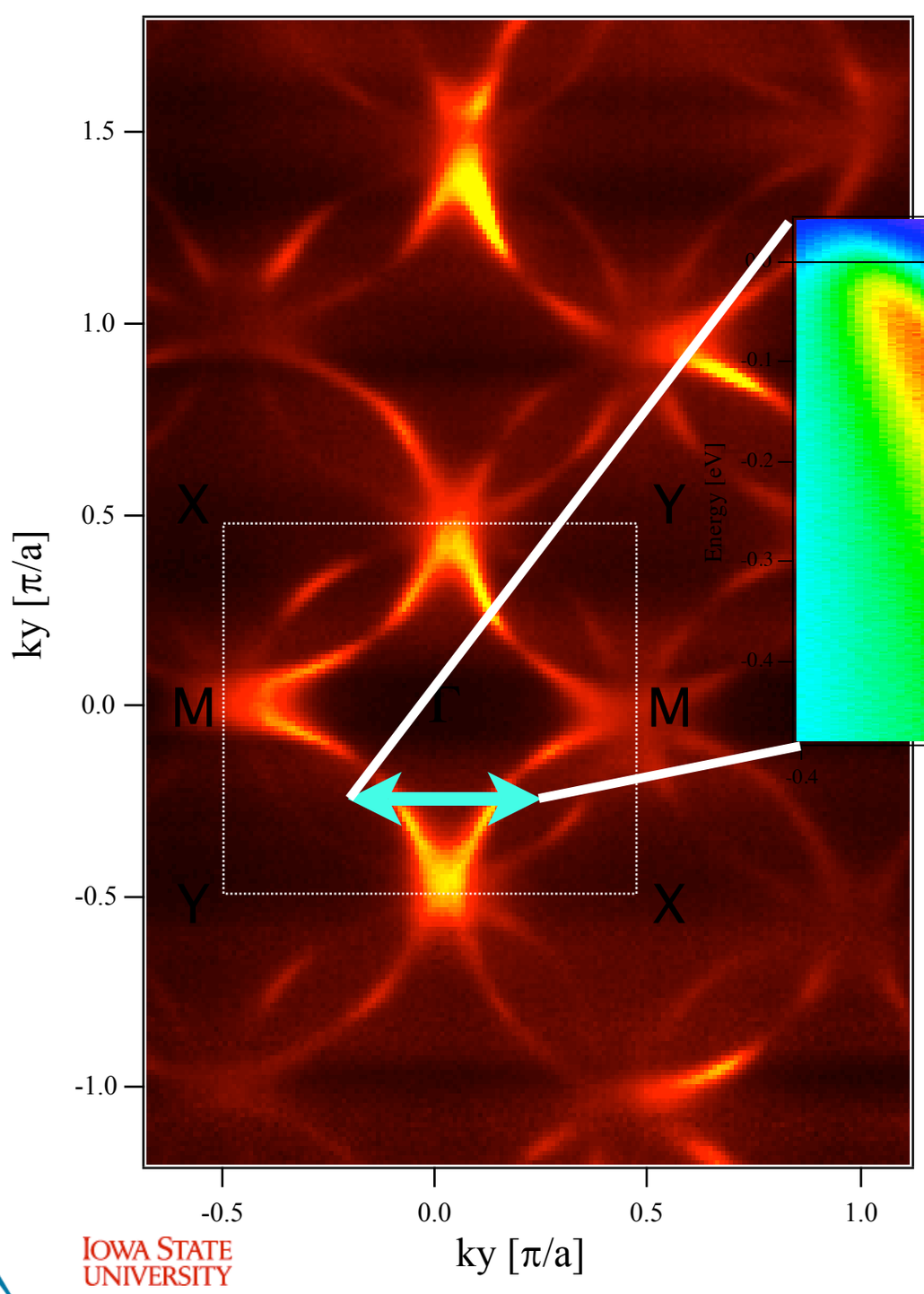
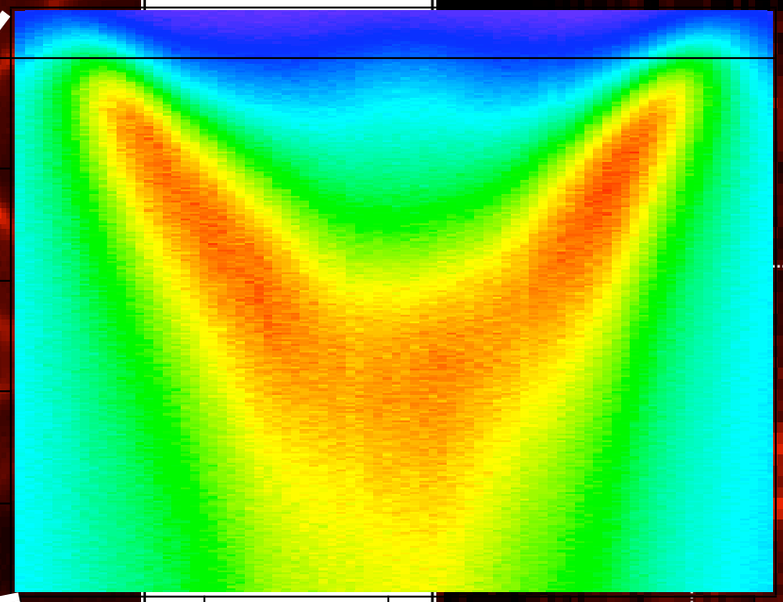
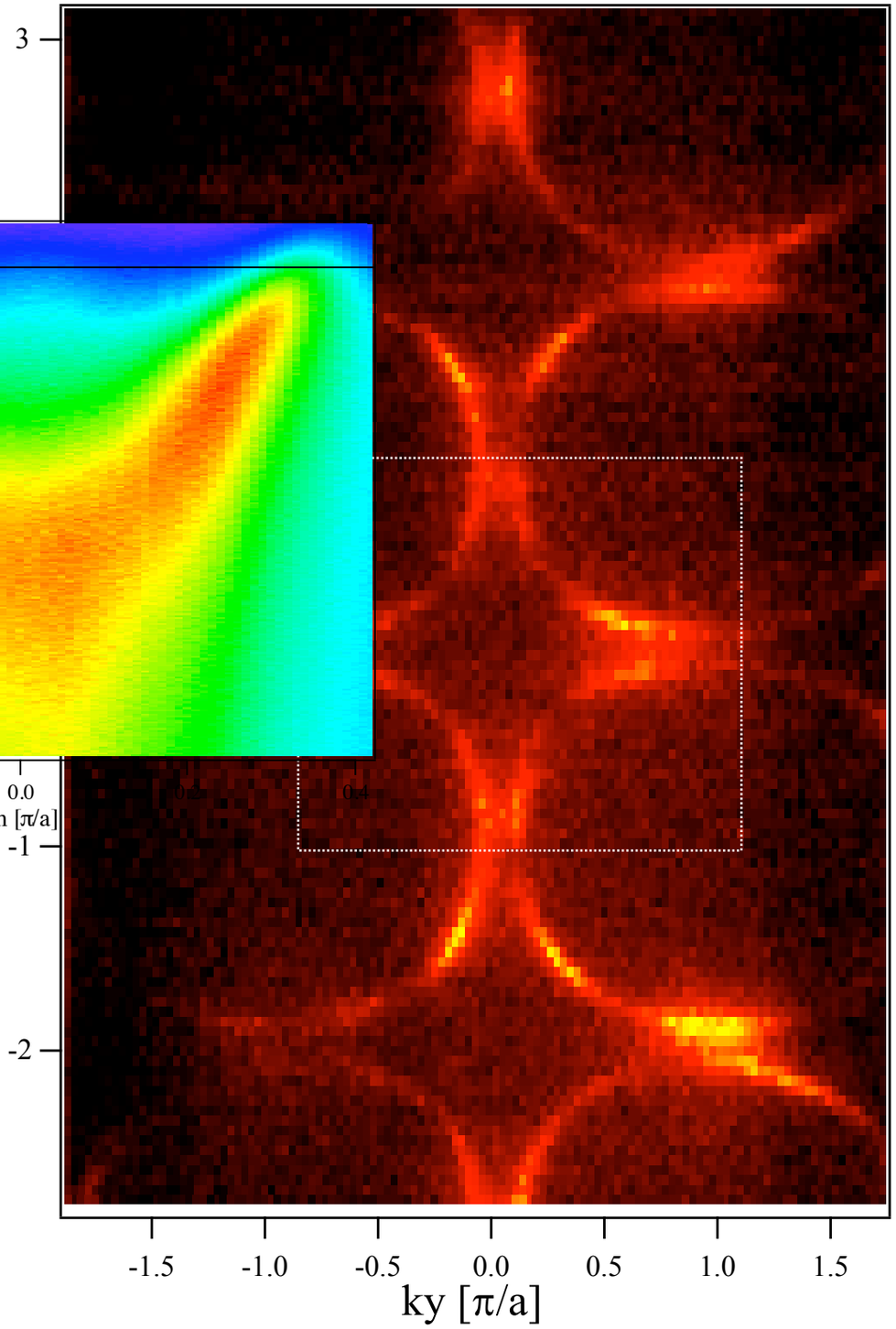
Fermi surface of high temperature superconductor

$Bi_2Sr_2Cu_1O_{6+x}$ (Tc=35K)





$Tl_2Ba_2Cu_1O_{6+x}$(Tc=90K)



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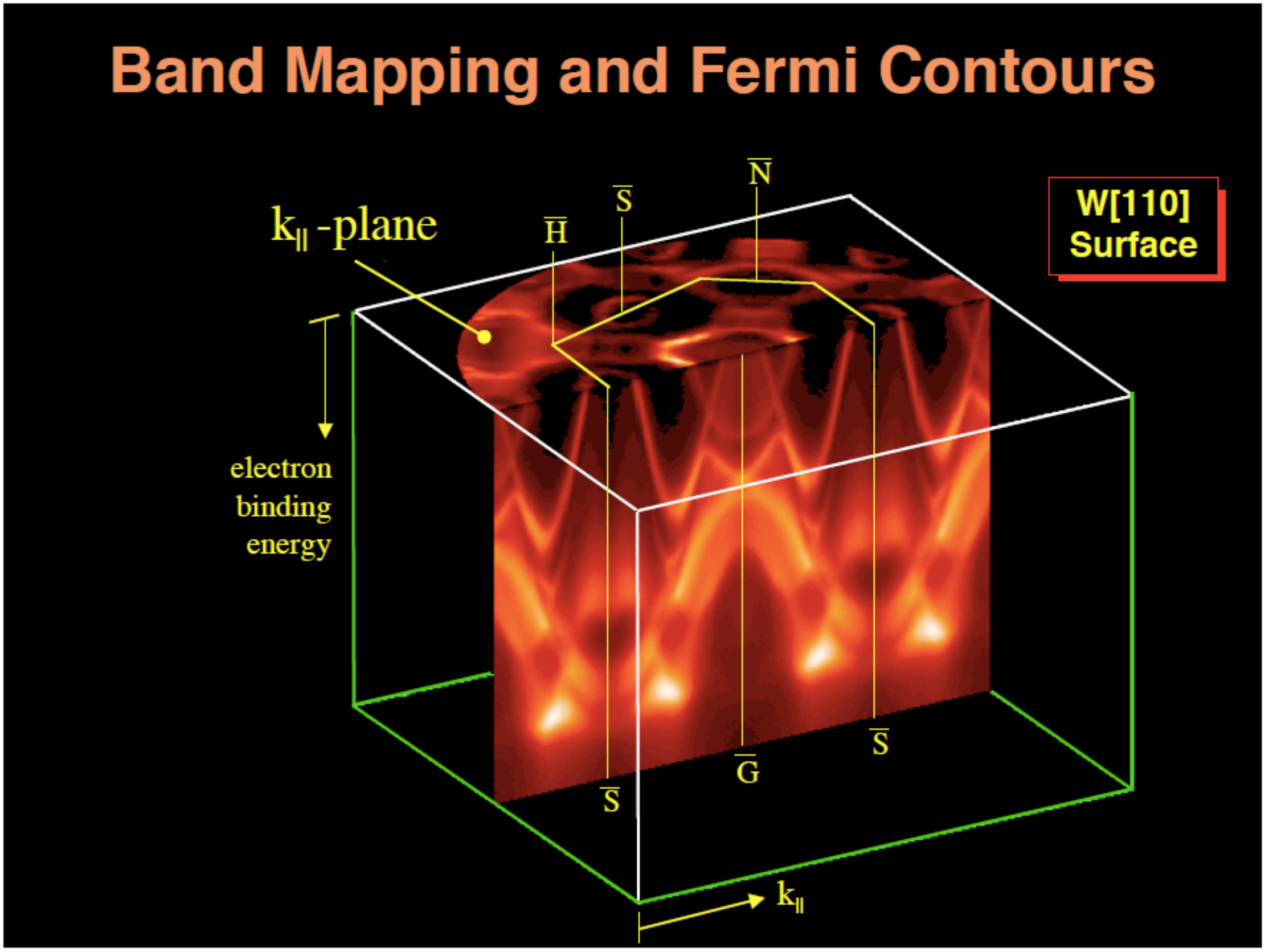
Band Mapping and Fermi Contours



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E. Rotenberg et al.

3D case:

$$k_{\perp}^{i} \neq k_{\perp}^{f}$$

$$V_0 - inner potential$$

$$|k^i| = \frac{\sqrt{2m(E_k + V_0)}}{\hbar}$$

$$k_{||} = \frac{\sqrt{2mE_k}}{\hbar} sin\theta$$

$$k_{\perp} = \frac{\sqrt{2m(E_k cos^2\theta + Vo)}}{\hbar}$$

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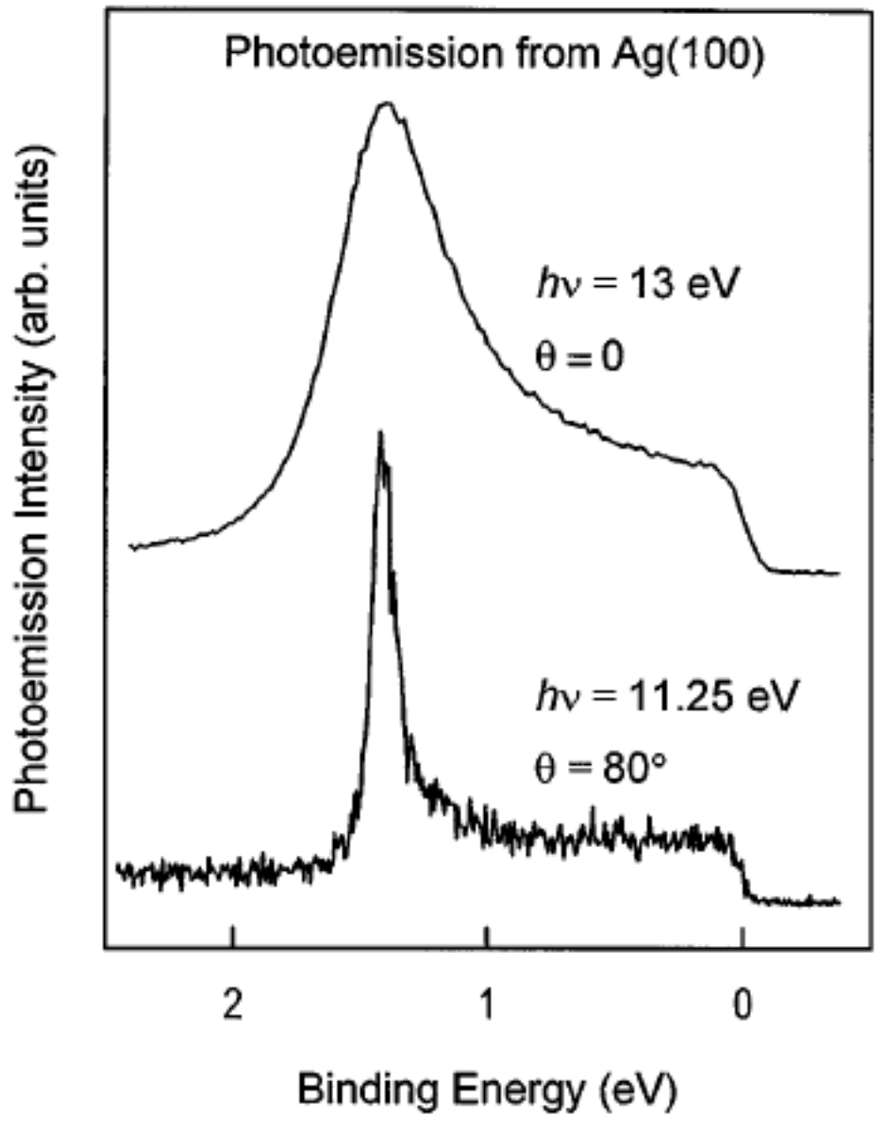
Width of the ARPES peak in 3D case

$$\Gamma = \frac{\frac{\Gamma_i}{|v_{i\perp}|} + \frac{\Gamma_f}{|v_{f\perp}|}}{|\frac{1}{v_{i\perp}}(1 - \frac{mv_{i||}sin^2\theta}{\hbar k_{||}}) - \frac{1}{v_{f\perp}}(1 - \frac{mv_{f||}sin^2\theta}{\hbar k_{||}})}$$

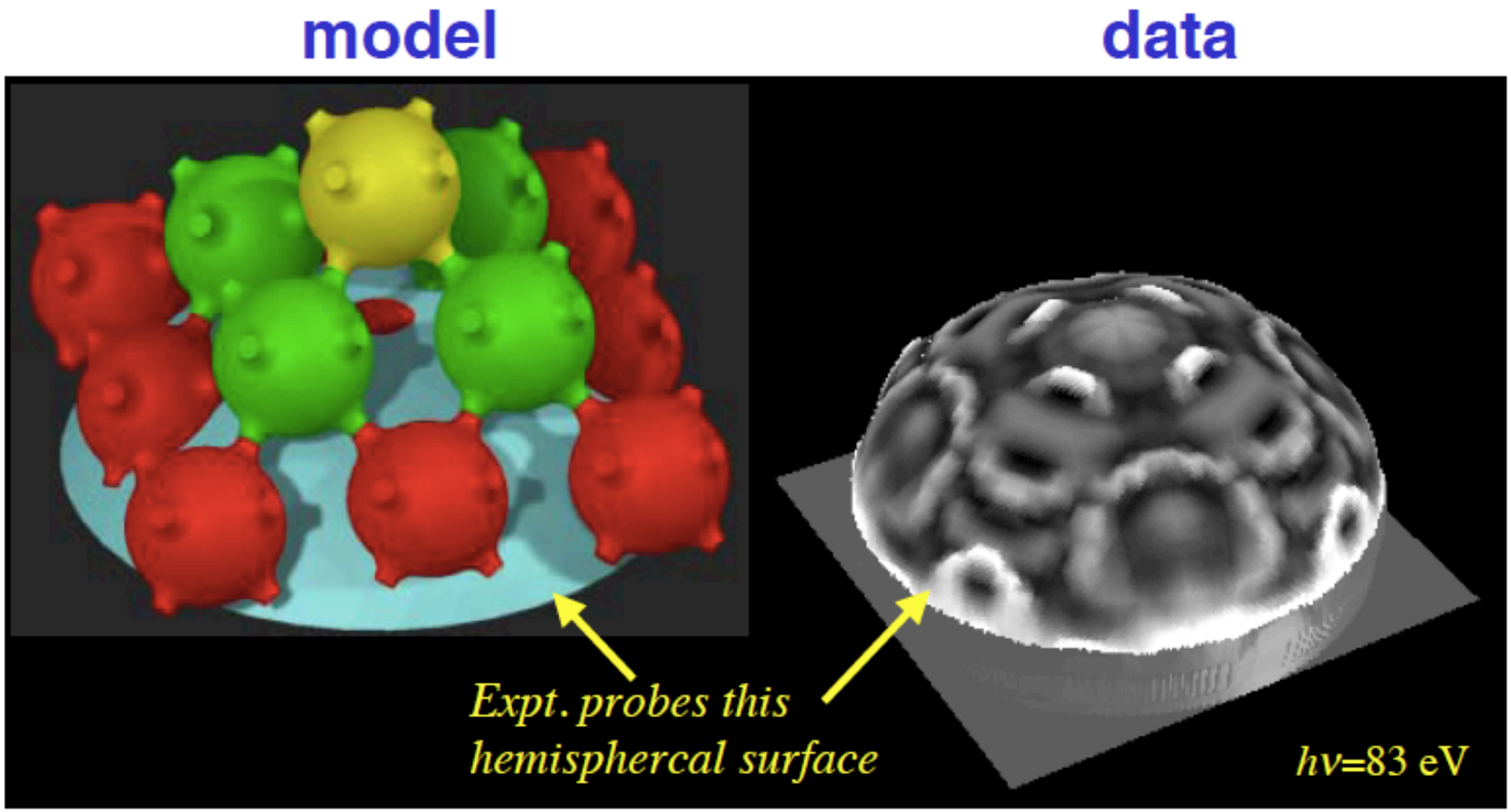
Width of the ARPES peak in 3D case

$$\Gamma = \frac{\frac{\Gamma_i}{|v_{i\perp}|} + \frac{\Gamma_f}{|v_{f\perp}|}}{\left|\frac{1}{v_{i\perp}}\left(1 - \frac{mv_{i||}sin^2\theta}{\hbar k_{||}}\right) - \frac{1}{v_{f\perp}}\left(1 - \frac{mv_{f||}sin^2\theta}{\hbar k_{||}}\right)\right|}$$



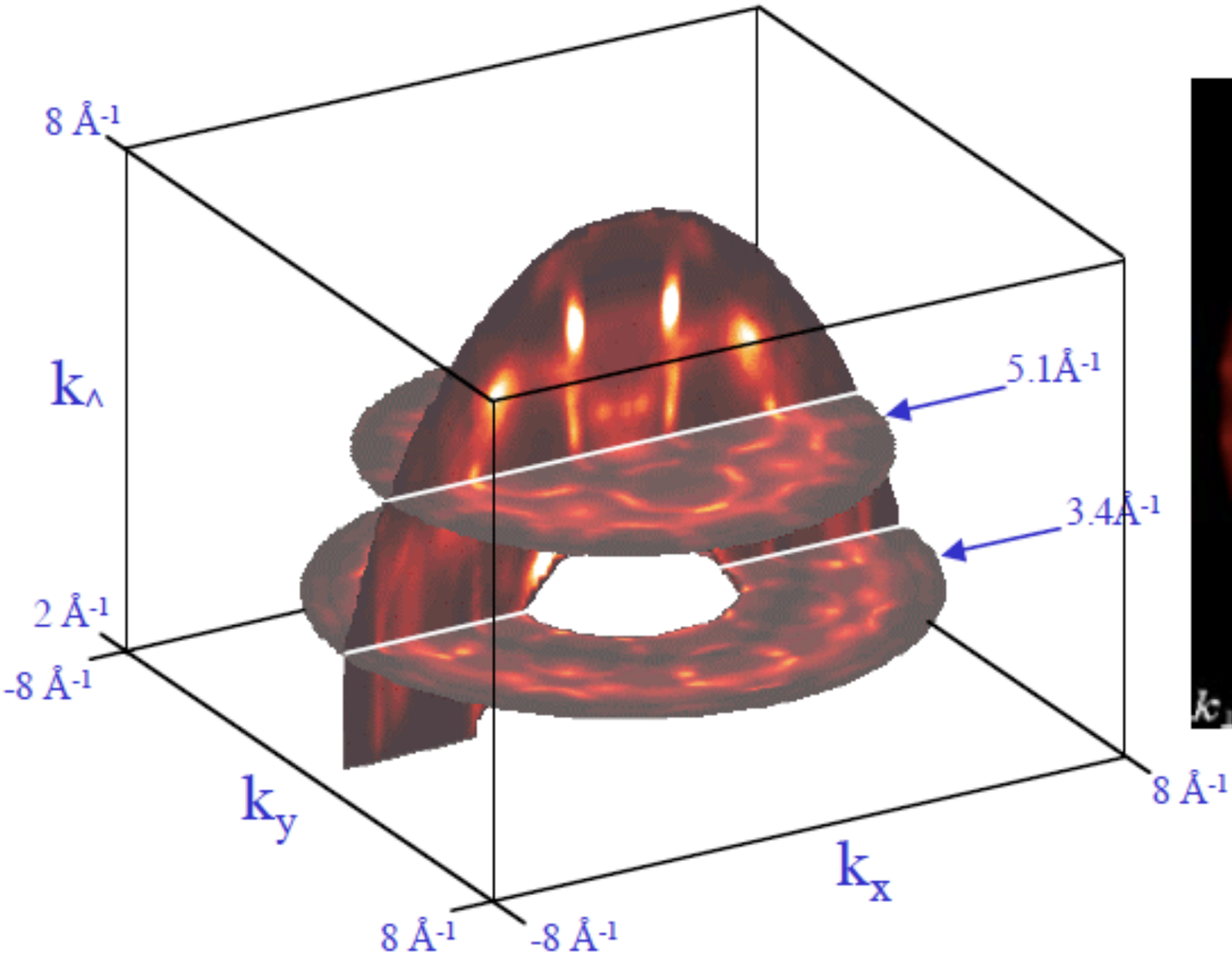
E. D. Hansen et al,
PRL 80, 1766 (1998)

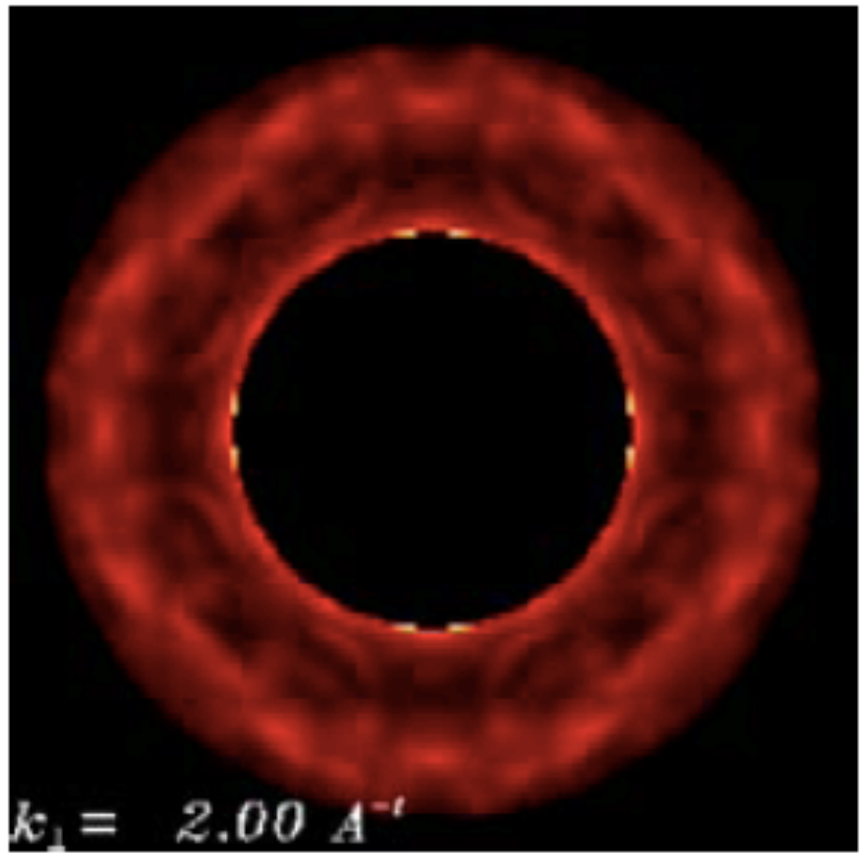
Example Cu:



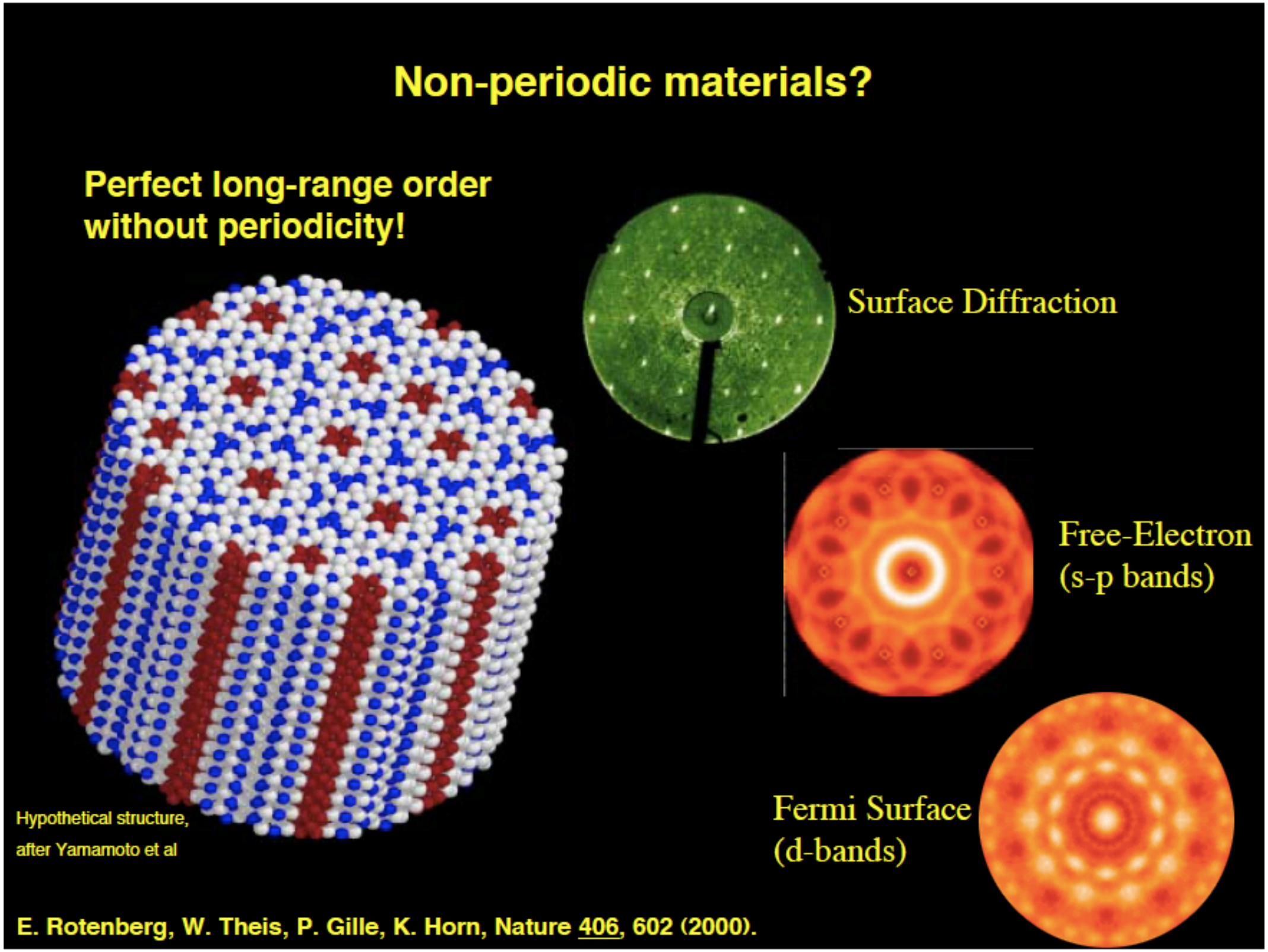
E. Rotenberg et al.

Example Cu:

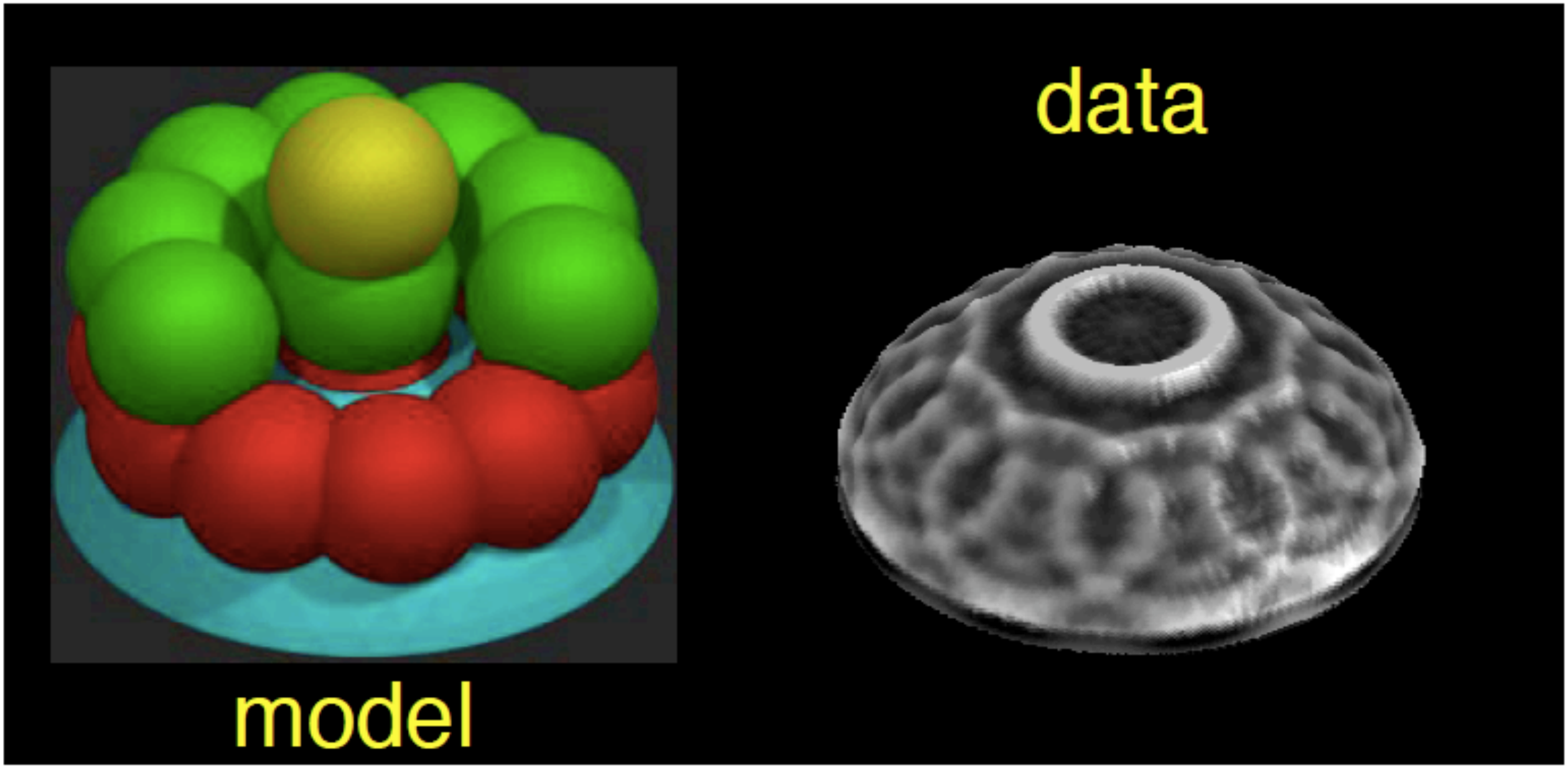




Quasicrystals:

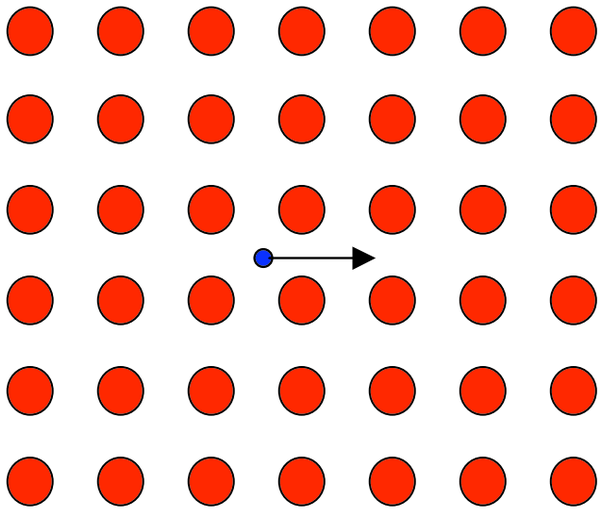


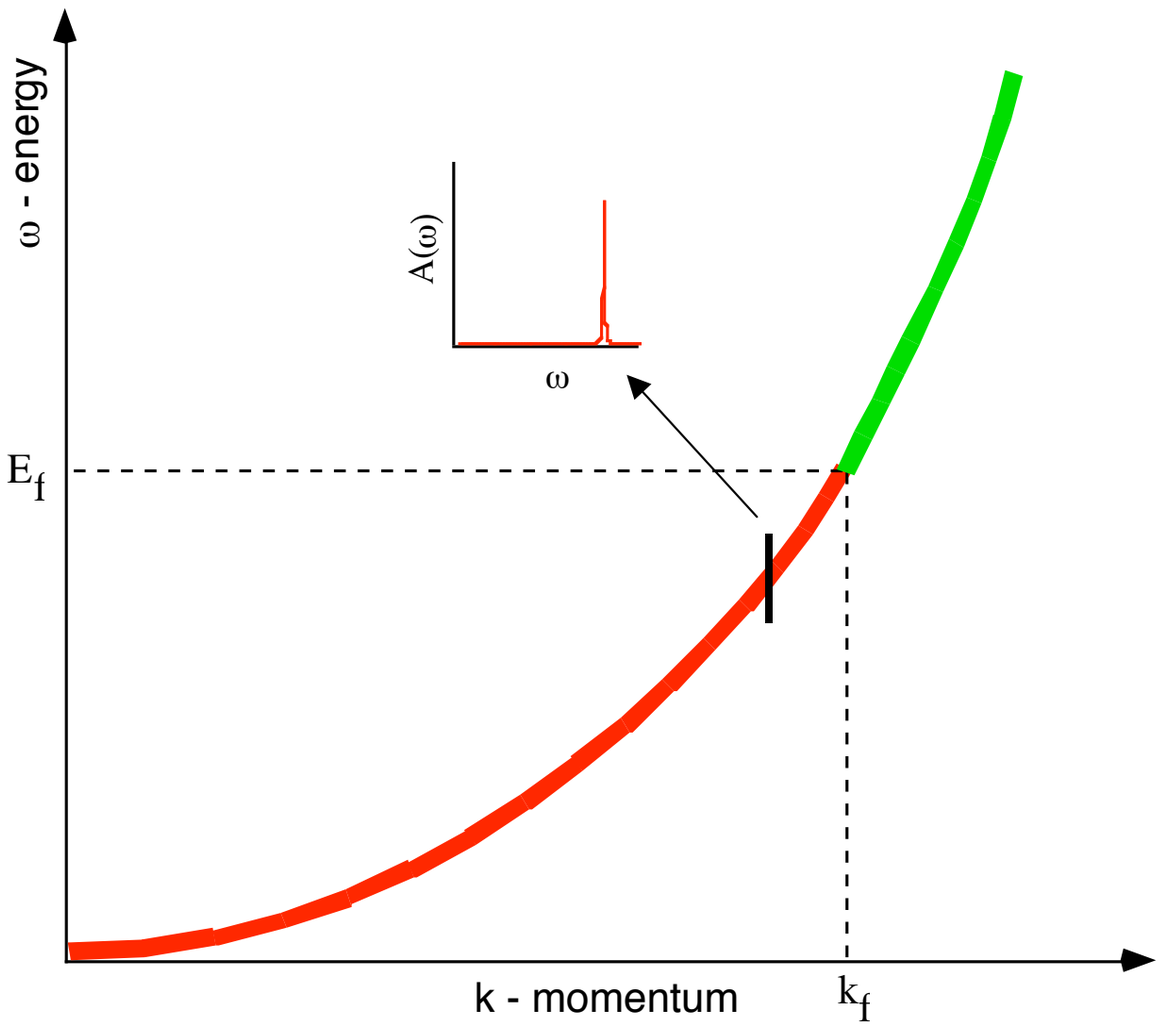
Quasicrystals:



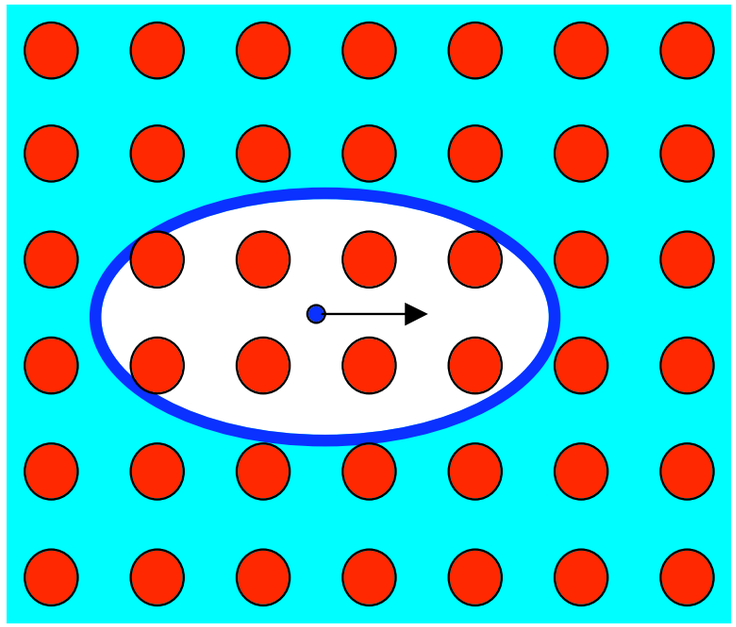
E. Rotenberg et al.

non-interacting electrons - free electron model





weakly interacting electrons - Fermi liquid model

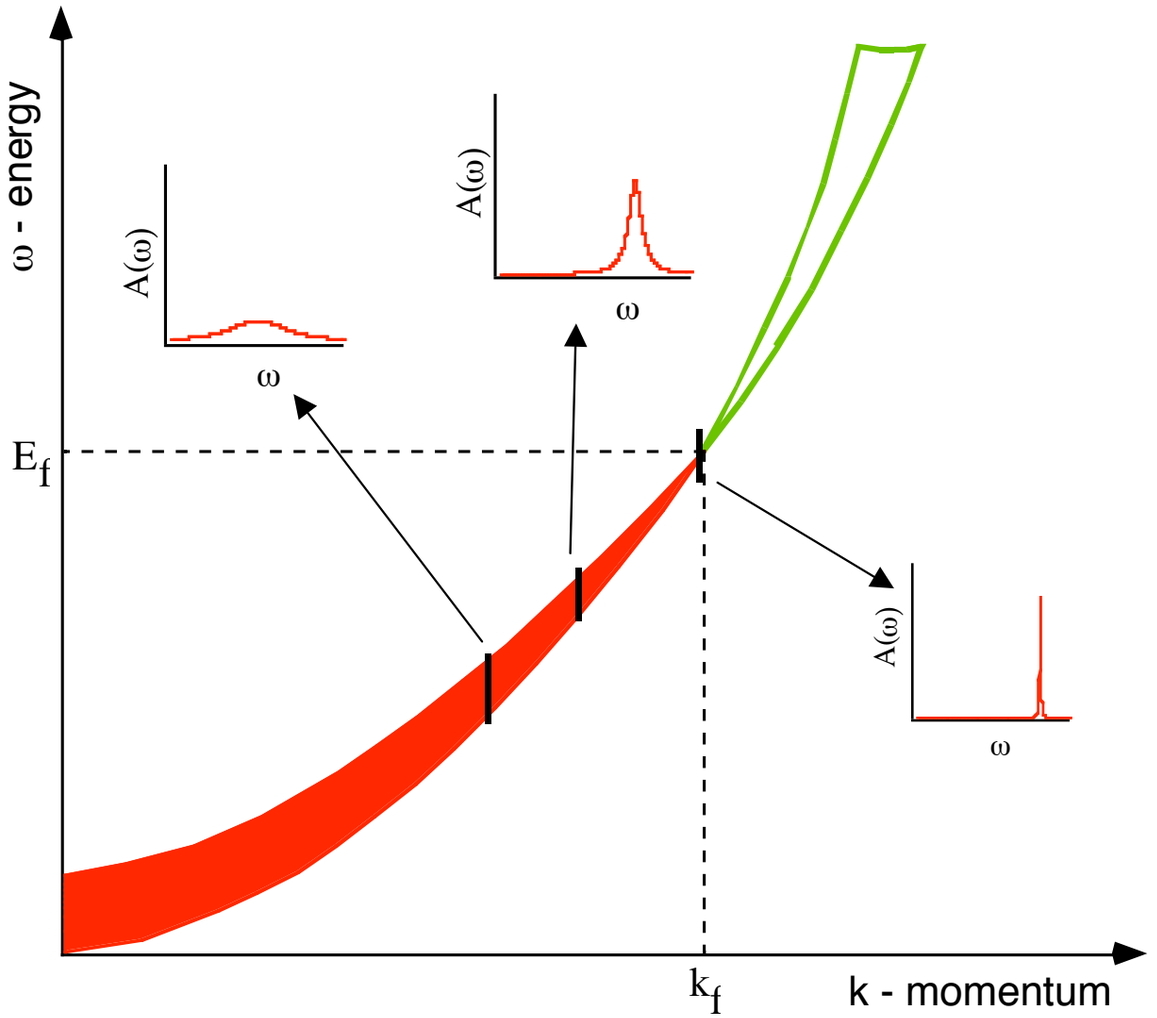


Quasiparticle="renormalized electron"

m^* , τ

Σ – self energy

$\Sigma(k,\omega)=\alpha\omega+i(\beta\omega^2+\gamma T^2)$



What does ARPES measure:

ARPES intensity

$$I = \langle \Psi_i | \boldsymbol{A}\cdot\boldsymbol{p} | \Psi_f \rangle^2 A(k,\omega)\, f(\omega)$$

symmetry of Ψ

electronic structure + interactions

Spectral function:

$$A(k,\omega) = Im(G(k,\omega)) = \frac{\Sigma''(k,\omega)}{(\omega - \epsilon(k) - \Sigma'(k,\omega))^2 - (\Sigma''(k,\omega))^2}$$

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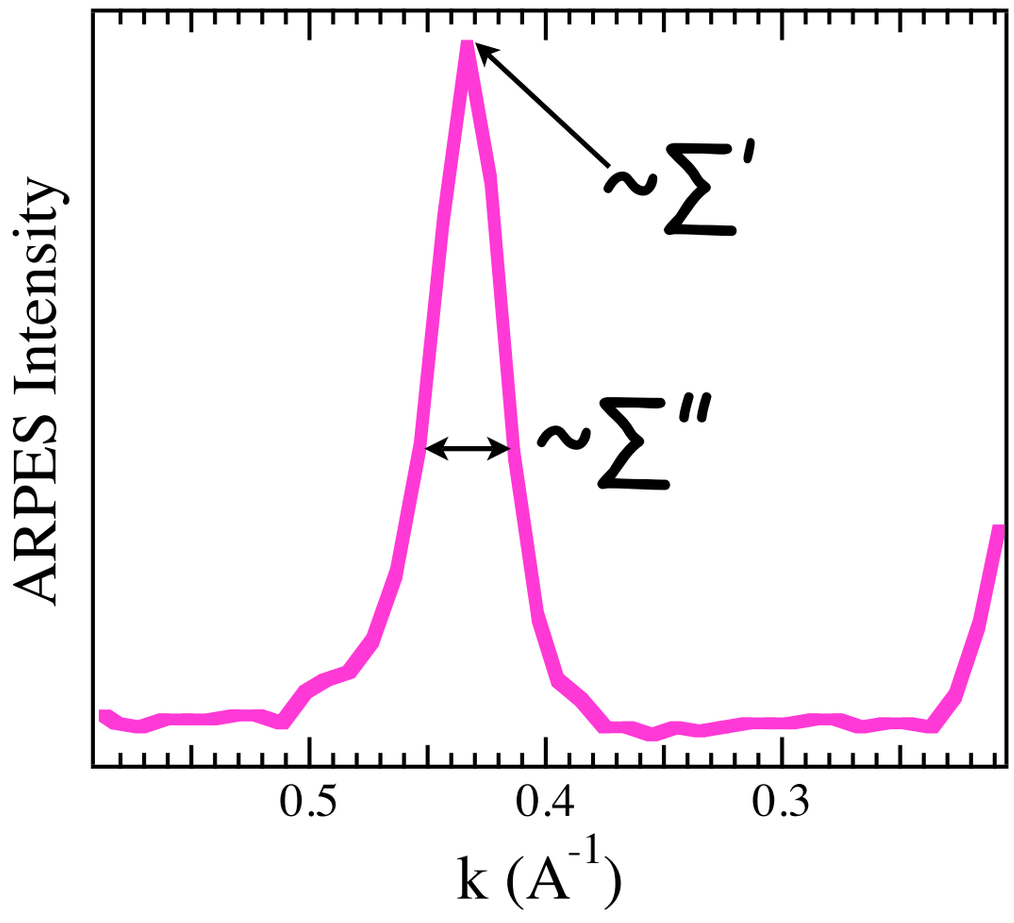
Self energy (=> scattering rate)

E=const

Momentum Distribution Curve

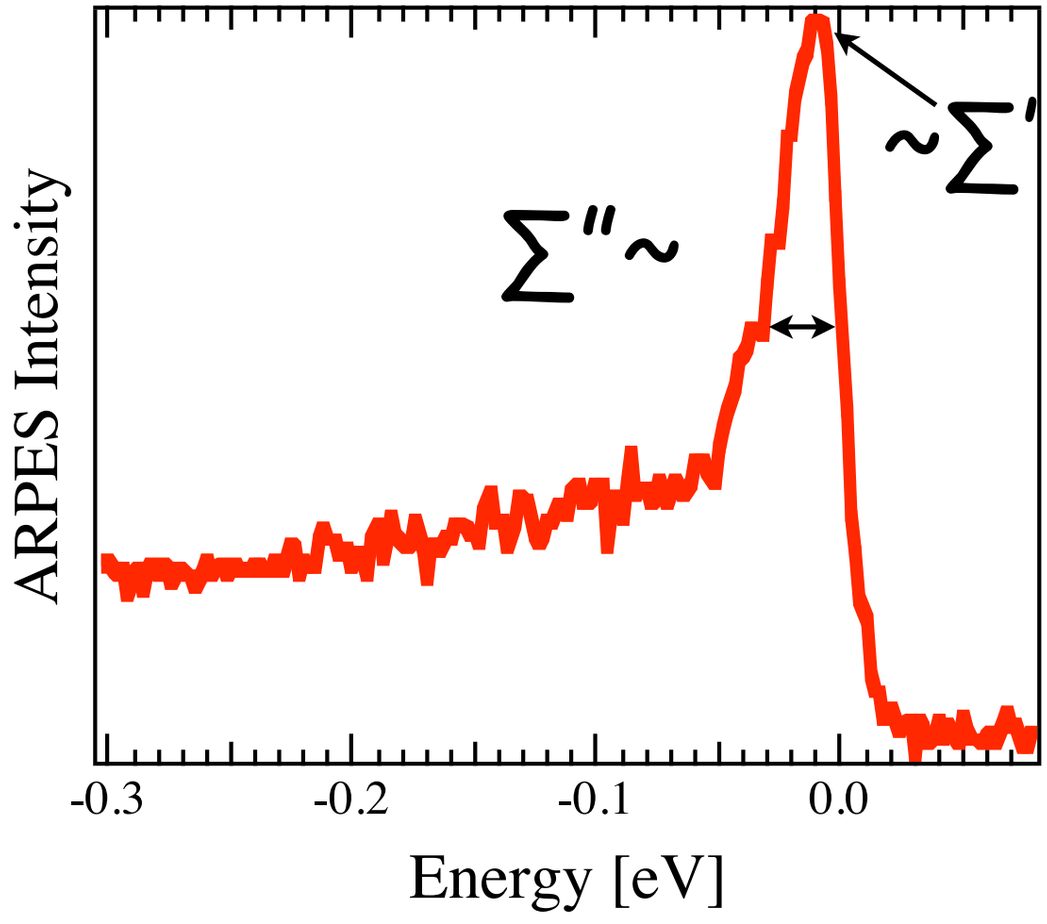
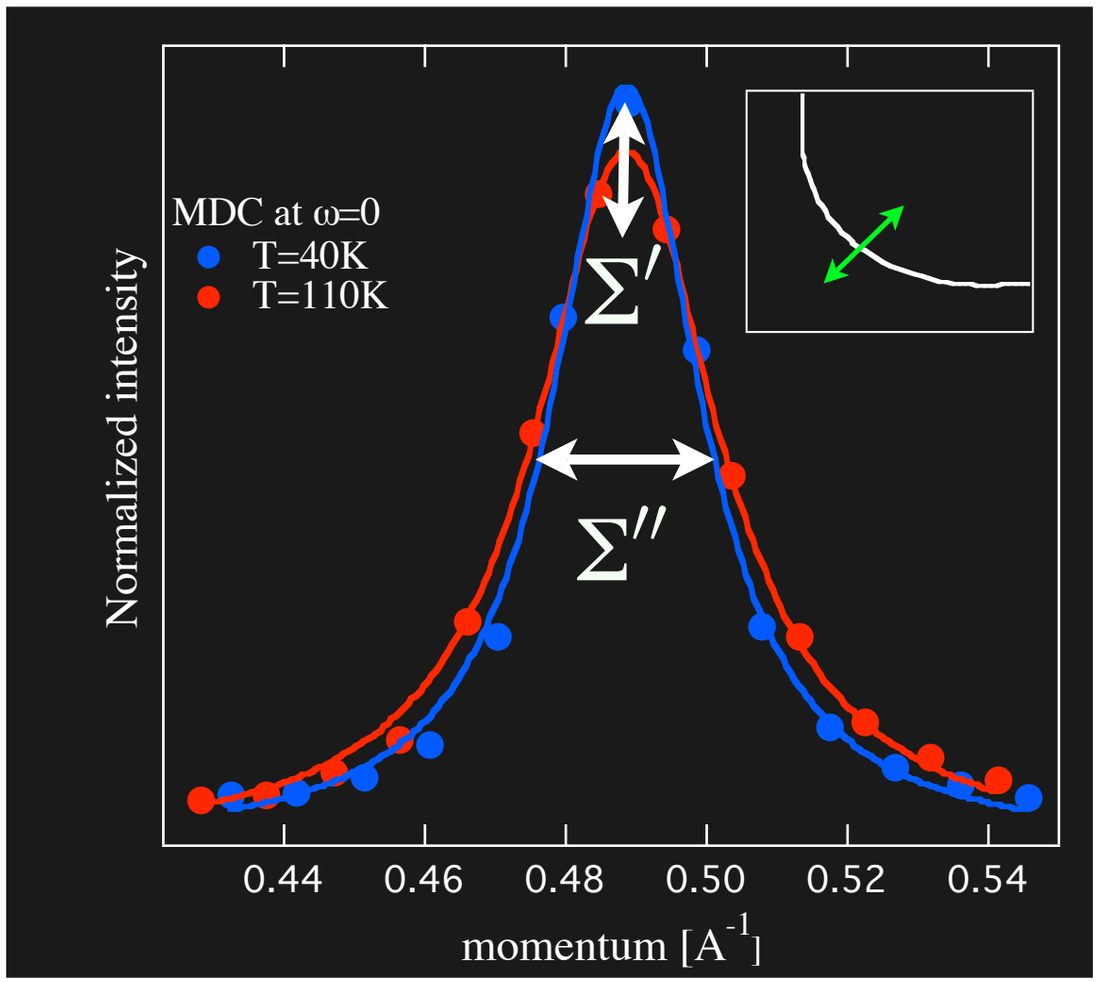
(MDC)



k=const

Energy Distribution Curve

(EDC)



$$A(k,\omega) = Im(G(k,\omega)) = \frac{\Sigma''(k,\omega)}{(\omega - \epsilon(k) - \Sigma'(k,\omega))^2 - (\Sigma''(k,\omega))^2}$$